RESEARCH ON A WEATHER SERVICE FOR SCHEDULING THE IRRIGATION OF WINTER WHEAT IN THE ORANGE FREE STATE REGION

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Research Report

to

THE WATER RESEARCH COMMISSION

by

DEPARTMENT OF AGROMETEOROLOGY

UNIVERSITY OF THE ORANGE FREE STATE

117/1/87

ISBN: 0 908 356 70 6

CONTENTS

CHAPTER 1

INTRODUCTION

GENERAL

Atmospheric conditions (the weather) primarily determine the water requirements of vegetative crops. It is only when water becomes limiting that soil physical properties and crop physiological characteristics assume a significant role. Hence, thorough understanding of atmospheric influences is imperative for an in-depth consideration of water use by crops. Thus, any investigation into irrigation scheduling must involve the weather.

Irrigation becomes necessary when, in response to atmospheric demands, the rate of water supply from the soil limits plant growth and hence production. The best method of analysing such a situation is via the use of a computer and the mathematical simulation of the natural process. It thus follows that irrigation scheduling could most effectively be undertaken using a computerized model which takes into account the weather. Such a technique provides a sound basis for determining the efficient use of irrigation water.

Particularly during the past three years of serious water shortages, has a premium been placed upon irrigation efficiency. It has furthermore, become necessary to strive towards obtaining maximum production from limited water supplies. The major losses in production are generally incurred as a result of poor cultivation practices. Coupled with this is bad irrigation management.

For example, untimely or inadequate irrigation can be responsible for depressing yield. Excessive irrigation producing deep percolation out of the root zone, on the other hand, is the prime cause of water wastage. There is little doubt that scheduling irrigation according to atmospheric demand should be practised as it will contribute to the alleviation of both these irrigation problems. Such technique will limit water losses due to incorrect assessment of the amounts of water required for successful economic production. The work described here is aimed at rationalizing the interaction of weather, plant and soil. This will be done in the computer in a manner making possible the scheduling and planning of irrigation. The work was conducted by means of cooperative experiments with farmers in the Hartswater district and on the experimental site of the Department of Agrometeorology, on the West Campus of the University of the Orange Free State.

THE CONCEPT OF EVAPORATION FROM A NATURAL VEGETATIVE SURFACE

Penman (1948) defined the term potential evapotranspiration as the evaporation from a short grass surface well supplied with water. The significance of the interaction between vegetative architecture and the atmosphere was then not fully realized. The implicit assumption was that evapotranspiration from all cropped surfaces could be referenced to short grass evaporation. However, crop height and shape seriously influence both the conductance of water vapour away from the surface, and the temperature of the surface. These markedly influence water removal from the vegetative surface. It is thus possible to find, for given sets of atmospheric conditions, different rates of potential evapotranspiration corresponding to different types of vegetative cover. To overcome this uncertainty and to account for the role played by evaporation from a soil surface under incomplete vegetative cover, the following definitions will be adhered to in this treatise.

The total evaporation from a natural vegetative surface, E, is defined as the sum of evaporation from the sub-stomatal cavities of leaves, Ev, plus the evaporation from the surface of the soil, Es. Thus

$$E = Ev + Es \qquad ..(1.1)$$

Transpiration is, in effect, the evaporation from the cell walls in the sub-stomatal cavity.

The term, maximum evaporation from a given crop replaces the term potential evapotranspiration. Thus, when soil water is capable of meeting atmospheric demand, the symbol Em will be used to denote maximum total evaporation from a specific crop surface in a given growth stage.

$$Em = Ev + Es \qquad ..(1.2)$$

Total evaporation and evapotranspiration are entirely synonymous. Although the term total evaporation (E) is here preferred; the term evapotranspiration (ET) will also be used. In which case the symbols in Eqn 1.2 become:

$$ETm = Tm + Es \qquad ..(1.3)$$

The above definitions follow proposals by Monteith (1985). He went on to emphasize that total evaporation (E) has the same number of syllables as evapotranspiration, occupies slightly less space on the printed page and, unlike ET, has no extra-terrestrial connotations.

The concept of evaporation from a short grass surface well supplied with water is recognized. Reference evaporation, Er, is defined as the evaporation from a short grass surface supplied with adequate water. Similarly evaporation from a large open water surface will be defined by the symbol Eo.

OBJECTIVES

A convenient way of scheduling irrigation on a number of neighbouring farms is via the use of weather data from a central station. These data should be representative of conditions occurring on the various farms. Such data may then be processed by computer to provide simulations of conditions on many individual irrigation plots in the area. Since such a technique is based upon estimations of actual atmospheric evaporative demand it leads to the most efficient use of water. The present project follows upon an initial project (De Jager, Van Zyl, Bristow and Van Rooyen, 1982) which developed a suitable computer programme with which irrigation scheduling could be managed more efficiently. This project takes the work one step further and investigates the practical application of the model.

The objectives of the project were to:

(i) prove the accuracy and viability of computer irrigation scheduling

(ii) demonstrate the application of a central computerized service for scheduling the irrigation of wheat on individual farms using weather data,

(iii) standardise the operational procedure for such a system,

(iv) install a large lysimeter and test the accuracy of various aspects of the simulation model used, in particular -

(a) the crop evaporation formulae, and

(b) crop hydraulic conductance relationships responsible for the onset of water stress utilizing, in addition, micrometeorological techniques and infra-red thermometry,

(v) further verify the leaf water potential and leaf area index sub-models.

NOTE: It had been the intention to construct two lysimeters, but finances limited the project to one. Data from Rietrivier Experimental Station were to have been used, but the drought made this impossible.

The investigation included cooperative field experiments and experiments on the Agrometeorological experimental site on the West Campus of the UOFS.

The research project commenced on 1 October, 1982.

CHAPTER 2

THE VALIDATION OF PUTU 9

PUTU 9 is the model developed in the previous project (De Jager *et al*, 1982). It was utilized in the first stages of this project. PUTU 9 was modified from an hourly time step model to PUTU 9.86 which works in daily time steps. However, it was deemed interesting and necessary to validate the initial model in order to determine problems that could be rectified in PUTU 9.86. Also, PUTU 9 may well be utilized in the future.

PROCEDURE

Essentially an accurate simulation model for scheduling irrigation must provide reliable simulation of crop water use and the onset of water stress. Relative evaporation is defined as the ratio of total evaporation (E) to maximum total evaporation (Em). The presence of crop water stress is indicated by a value of relative evaporation less than unity. Hence a scenario of E/Em versus time clearly illustrates when the onset of stress took place and permits quantitative comparisons between measurements and simulation. Accurate simulation of measured total evaporation by a model produces a suitable validation of a crop water use model. Evaporation models have to be validated for both bare soil (Es) and cropped surfaces (E).

The necessary measurements were made and simulations carried out in the 1984 and 1985 seasons on West Campus. Measured values of evaporation were obtained from the lysimeter. Automatic weather station data were utilized to simulate E and Em.

For both years, the scenario of the simulated and measured ratio are illustrated in Figs. 2.1 and 2.4. Comparisons between measured and simulated daily crop water use, E, are shown in Figs. 2.2, 2.3 for bare soil conditions, and in Figs 2.5 and 2.6 for the wheat crop. Simulation indices, SI (Willmott, 1982), and correlation coefficients were calculated and are shown in each of the relevant figures. A simulation index of SI = 0,7 generally indicates acceptable accuracy in biological experiments.

Figs 2.2, 2.3, 2.5, and 2.6 do not include days on which irrigation took place because it was not possible to determine evaporation from the lysimeter without an accurate measurement of the rainfall or irrigation in the lysimeter. In 1984 and 1985, rainfall and irrigation amounts were estimated directly from the lysimeter record.

RESULTS AND DISCUSSION

The figures and statistical tests indicate that reasonable agreement between simulated and measured values were obtained. The simulation indices were acceptable for bare soil conditions in both years. For the wheat cover, the model proved to be acceptably accurate in 1985 (SI = 0,89) but less acceptable in 1984 (SI = 0,69).

The accentuated scatter in particularly Fig. 2.2 and 2.5 is due to an inadequate resolution setting on the datalogger used. Fig. 2.4 indicates that under incomplete vegetative cover (DOY 234 to 250) in 1984, PUTU 9 over estimated E. The same was partially true from DOY 213 to 235 in 1985. Furthermore, with full canopy, DOY 275 to 330 in 1984, PUTU 9 predicted stress which was not evident in the lysimeter readings. The crop coefficient (F) for simulating the degree of stress in PUTU 9 is defined by

$$E = F.Em$$

where,

$$F = [Fle \ . \ Fh + Fg.(1-Fle)]. \qquad ..(2.1)$$

These three F-terms are dimensionless constants between zero and unity. Originally they were described as follows:

Fle = -0,2 + 0,7 LAI (Ritchie, 1972) where LAI = leaf area index,
Fh = 1/ [1 + Exp (PSIC - PSIL)] and
Fg = EXP [0,4. days since surface was wetted]
PSIL and PSIC are leaf water potential and stress threshold leaf water potential respectively.

Evaporation from the soil, Es, was computed from

$$Es = Fg.(1 - Fle).Em \qquad ..(2.2)$$

Hence, for bare soil, Es = Fg . Em

The initial over-estimation of E for an incomplete vegetative cover could have been due to use of the Ritchie (1972) equation. A better estimator might be obtained by replacing Em by Er. Trial and error methods were employed to rectify these problems. These suggested replacing the Ritchie (1972) equation by

$$Fle = 0{,}186.LAI \text{ for } Fle < 0{,}9, \text{ and} \qquad ..(2.3)$$

$$Es = Fg.(1 - Fle).Er \qquad ..(2.4)$$

The equation describing evaporation from bare soil which will be developed in Chapter 7, viz.

$$Fg = EXP(-a \,.\, VDEF1) \qquad ..(7.3)$$

where a is a constant, was used while establishing Eqn 2.3. Thus, in both the PUTU 9 and PUTU 9.86 runs of 1984 and 1985 Eqn 7.3 replaced the original Fg = EXP(-0,4.time).

Meyer and Green (1981) reported F values for a full wheat canopy varying between 1,1 and 1,3. Maximum total evaporation (Em), however, was estimated using the normal Penman equation with daily mean weather data. This probably under estimated Em under windy conditions for crop heights of approximately 0,7 m.

From Fig. 2.4. it appears as if the model predicts the onset of stress too early. This could also have resulted from the over prediction of E earlier in the season which would simulate more rapid depletion in soil water reserves.

CONCLUSION

PUTU 9 with Eqn 7.3, for determining the fraction of reference evaporation evaporated from a bare soil surface, was shown to be reliable. Use of this equation for bare soil throughout the period 1 March to 30 June yielded a SI > 0,77.

The model, PUTU 9, was considered to have reliably computed water use by the wheat crop in 1985 (SI = 0,89) when little water stress occurred. The poor performance in 1984 was ascribed to the model being over sensitive to stress. It was attempted to rectify this in PUTU 9.86 (the daily version of PUTU 9) by using an exponential root distribution and by iterating for leaf water potential and transpiration rate (see Chapter 4).

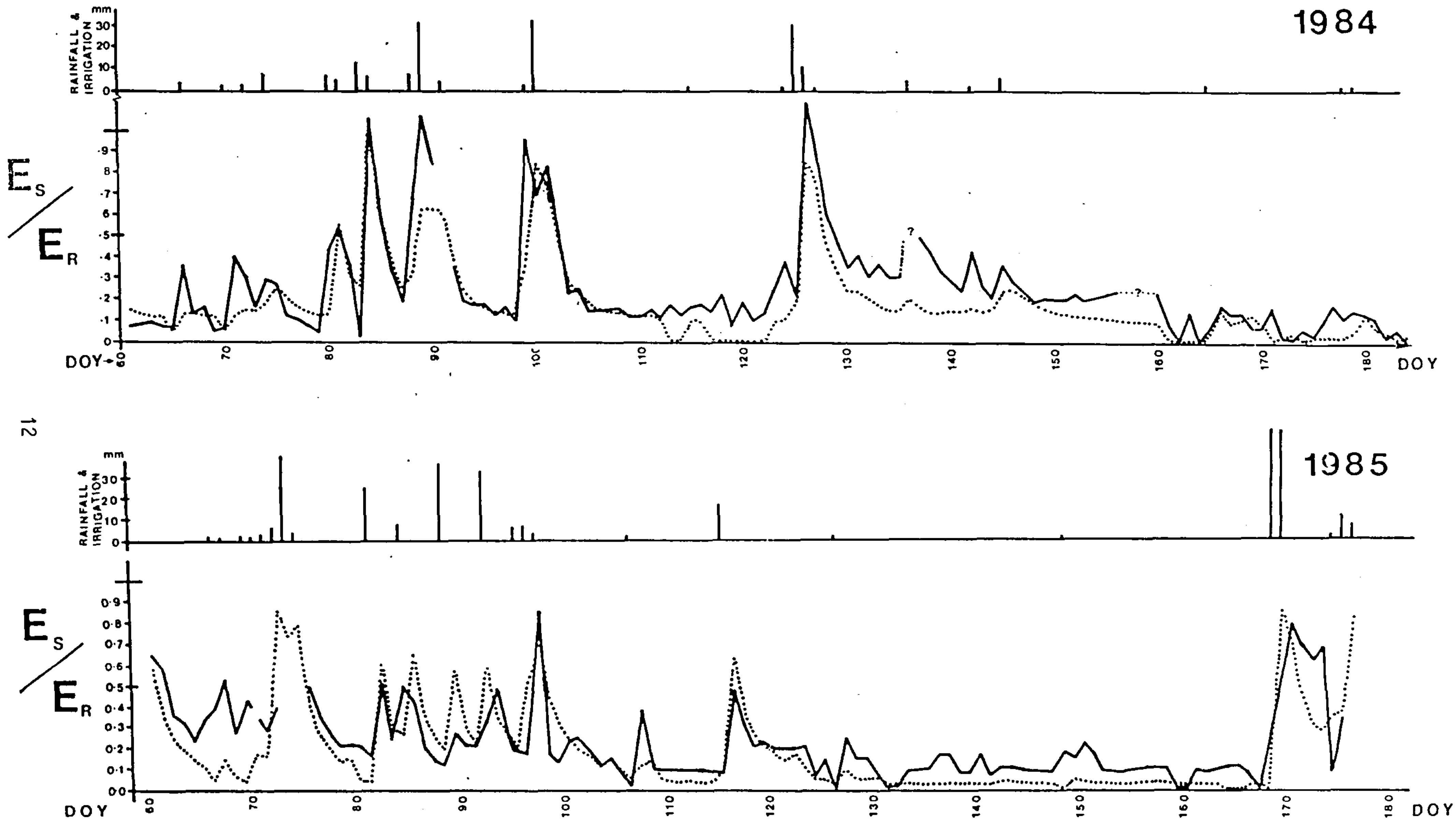


FIG. 2.1 - Measured (———) and simulated (......) scenarios of the ratio of evaporation from a bare soil to reference evaporation on West Campus during 1984 and 1985. Simulations were undertaken with PUTU 9.

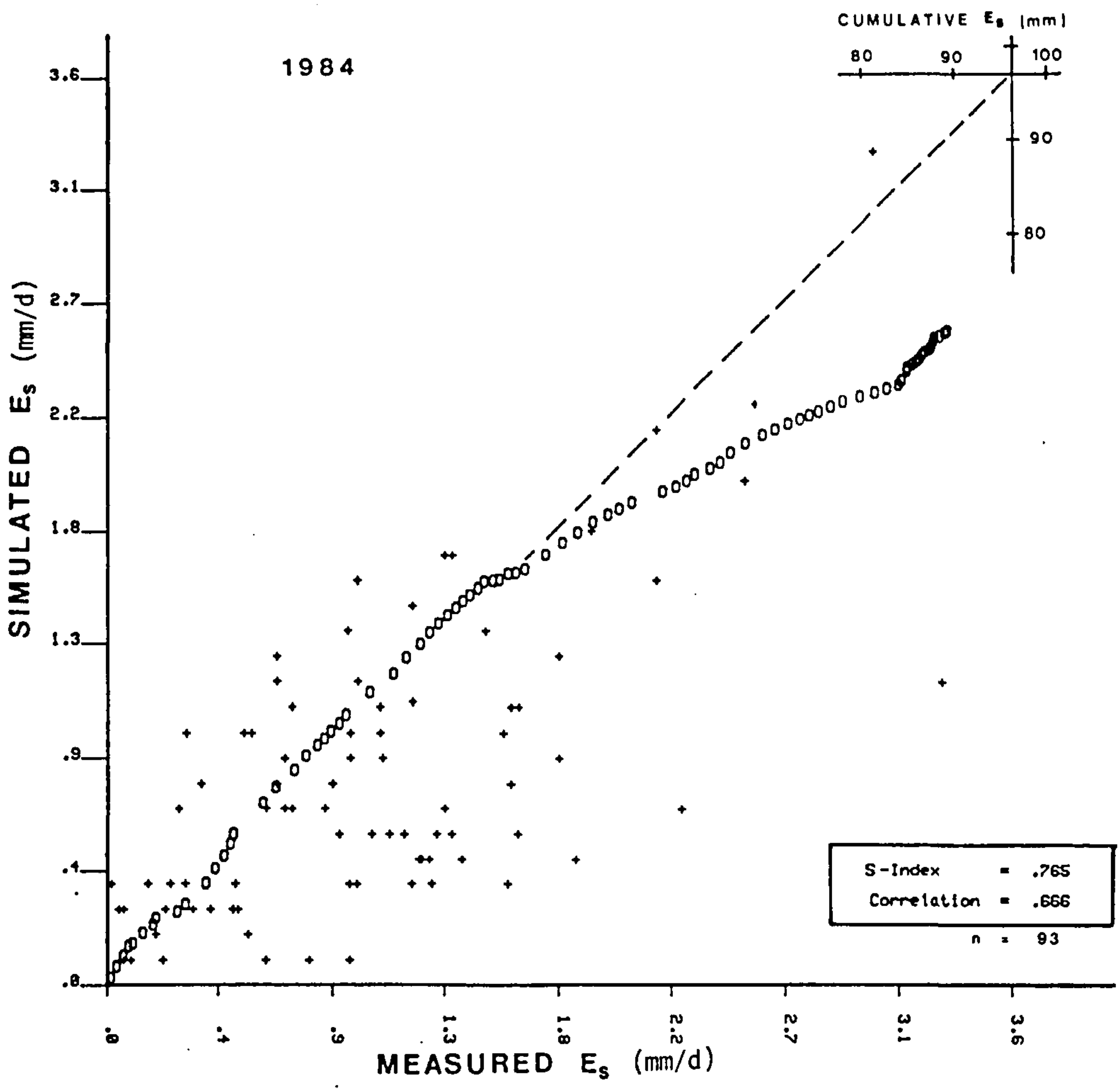


FIG. 2.2 - Relationships between cumulative (o) and daily (+) measured and simulated (by PUTU 9) evaporation from a bare soil during 1984 on West Campus.

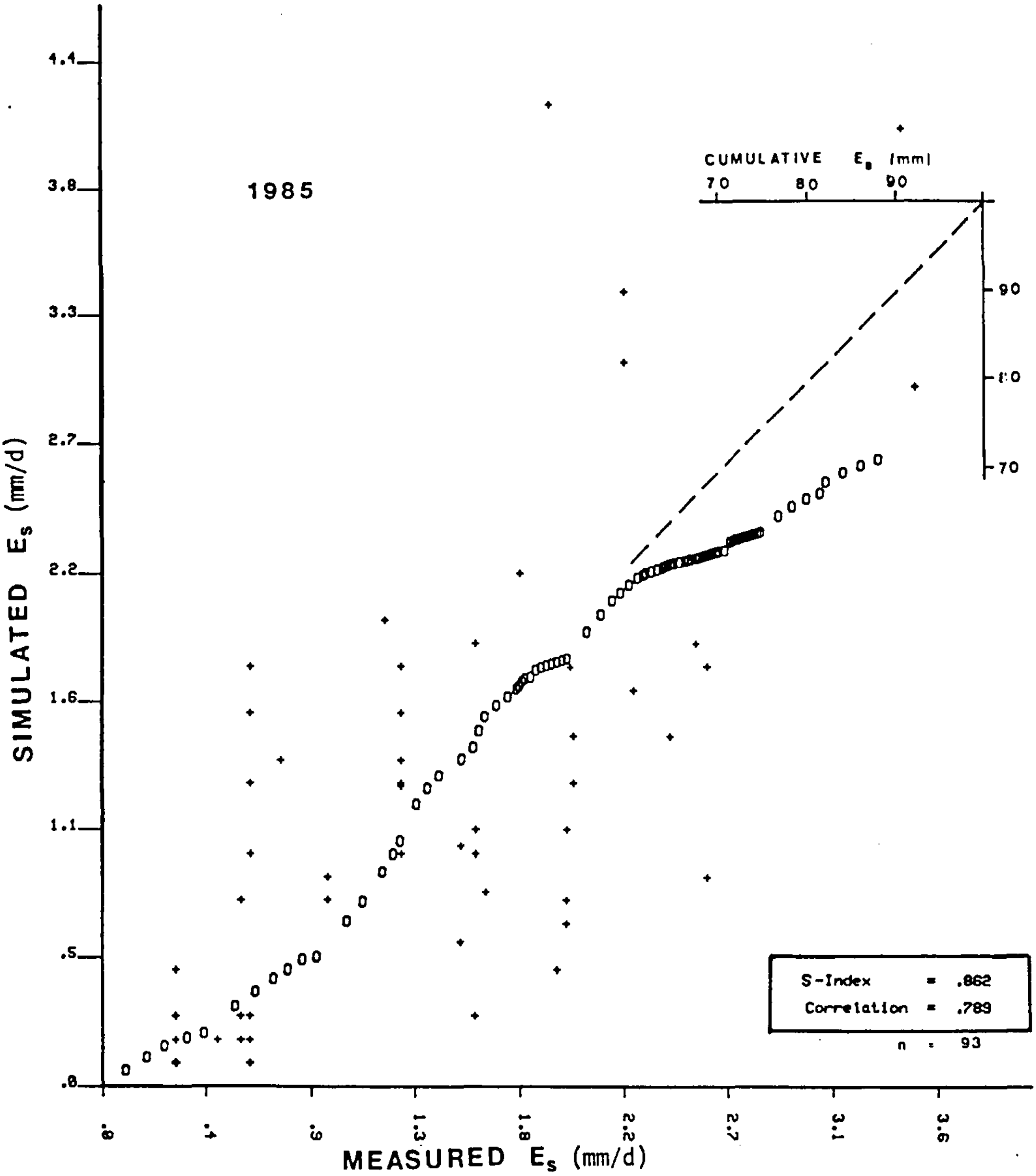


FIG. 2.3 - Relationships between cumulative (o) and daily (+) measured and simulated (by PUTU 9) evaporation from a bare soil during 1985 on West Campus.

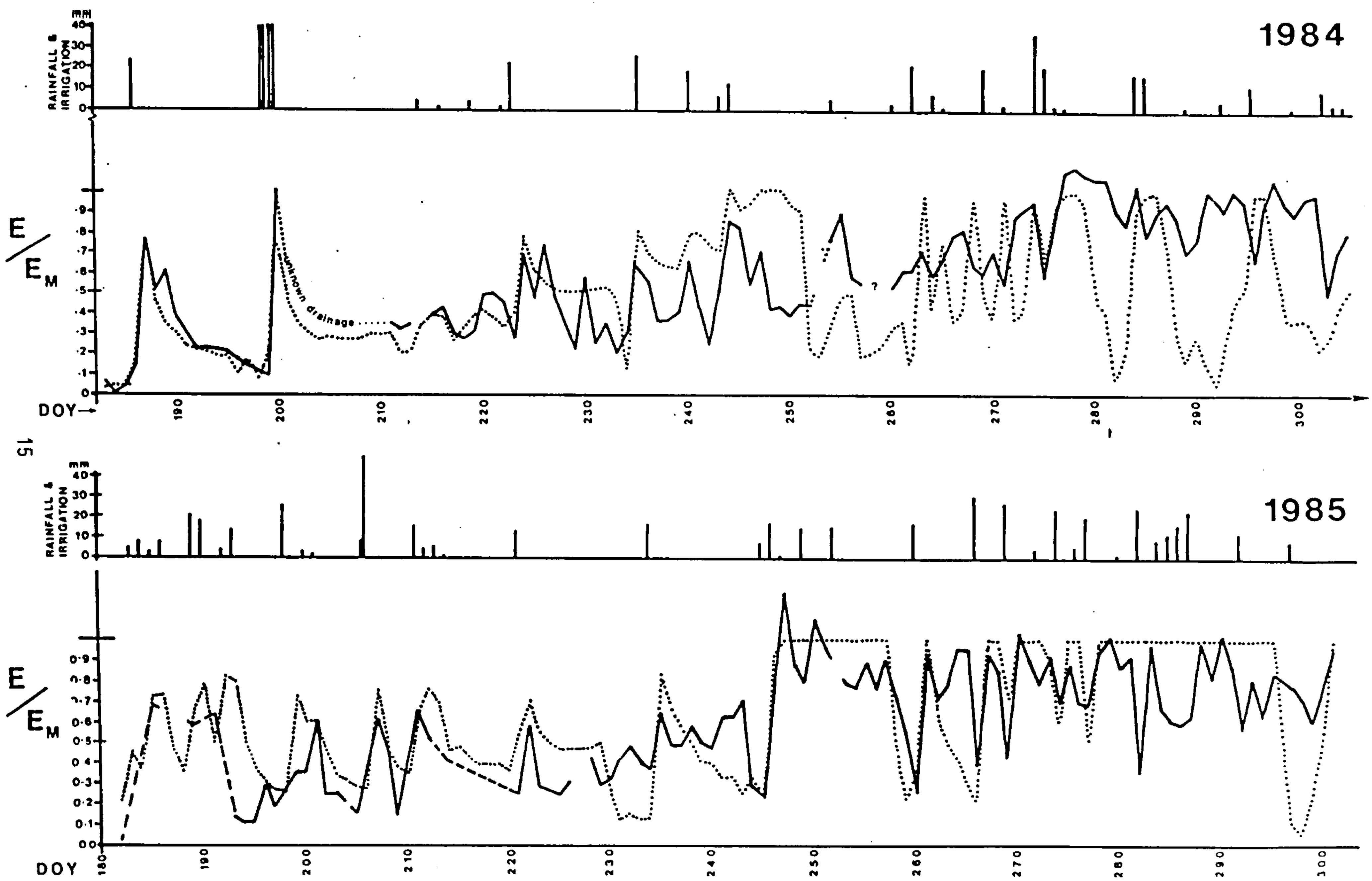


FIG. 2.4 - Measured (———) and simulated (......) scenarios of the ratio of total evaporation, E, to maximum evaporation, Em, on West Campus during 1984 and 1985. Simulations were conducted using PUTU 9.

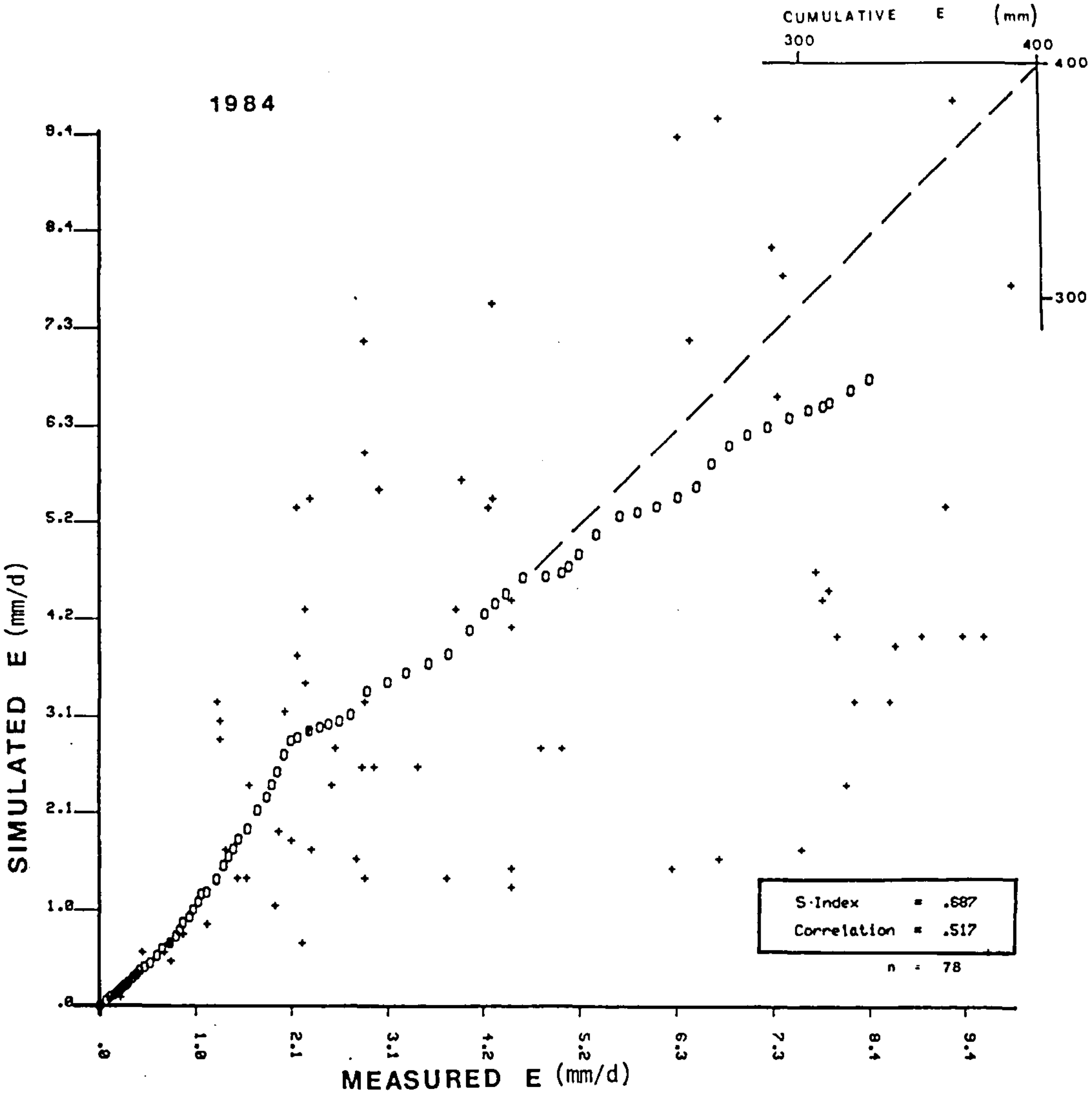


FIG. 2.5 - Relationships between cumulative (o) and daily (+) total evaporation from a wheat crop as measured and simulated (by PUTU 9) during 1984 on West Campus

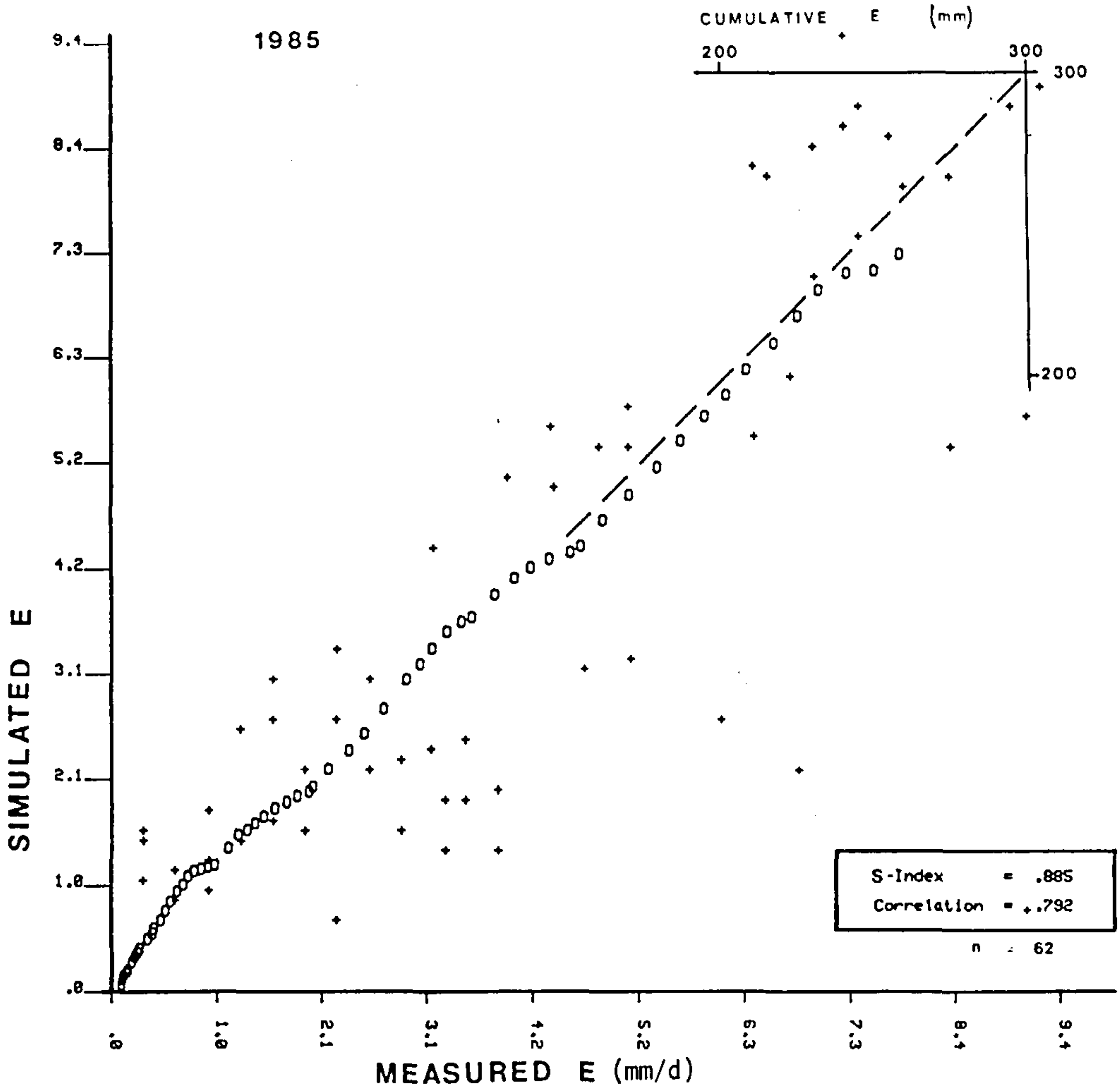


FIG. 2.6 - Relationships between cumulative (o) and daily (+) total evaporation from a wheat crop as measured and simulated (by PUTU 9) on West Campus during 1985.

CHAPTER 3

THE DESCRIPTION OF PUTU 9.86

The PUTU model was first created for maize in 1973. Its initial construction was described by De Jager (1974) and De Jager and King, (1974). The computing stages (modules) are described in Fig. 3.1. In the model the partitioning of dry matter proceeds as described in Fig. 3.2. A version of PUTU specifically for wheat, PUTU 6, followed in 1981. All the important functions for this model are described by De Jager, Botha and Van Vuuren (1981).

PUTU 6 was modified for irrigation scheduling and re-named PUTU 9. It is described in detail by De Jager <u>et al</u>., 1982. While PUTU 9 utilizes most of the functions of PUTU 6 it computes hourly time steps. It has subsequently become apparent that daily time steps are adequate, and necessary, where irrigation scheduling is concerned. Hence, the daily irrigation version PUTU 9.86 was developed. Computation of daily values of Em and Er from the hourly data from the automatic weather station was carried out using the programme in Appendix VI.

An attractive feature of PUTU models is their modular construction. During 1986 the computer programme was completely restructured and simplified to make the sequence of operations described in Fig 3.1 and 3.2. easy to follow. The main programme for PUTU 9.86 reads:

```
5  '******************************************************************
10    'PUTU9-86        NAAM:PUTU9-86        OP DISK:PROGRAM #2
20     LPRINT "Latest up-date on   1986.08.19 "
25 '******************************************************************
29  '
30    OPTION BASE 1
40    DIM X(366,8),GMT(12),GMR(12),GMS(12),GME(12),MONL(12),MEND(12),
      DOYMES(12)
50    '
60    GOSUB 2500                                       'MEAN DATA
62    GOSUB 15000                                      'FUNCTIONS
64    GOSUB 9500                                       'INITIAL CONDITIONS
72    GOSUB 10500                                      'WEATHER DATA INPUT
75    GOSUB 3100                                       'PARAMETERS
80    GOSUB 10000                                      'ZERO
85    GOSUB 5000                                       'TITLE PAGE
86    '
90                  '*************************
100                 'BEGINNING OF CALCULATION
101                 '*************************
130   '
170   FOR D = BEGIN TO FINISH
172   '
180      GOSUB 5500                                    'ENVIRONMENTAL VARIABLES
190      GOSUB 6000                                    'WATER BALANCE
200   IF STAGE > 1 THEN 230
210      GOSUB 1400                                    'PREREST PERIOD
220      GOTO  540
230   IF STAGE > 2 THEN 260
240      GOSUB 1500                                    'REST PERIOD
250      GOTO  520
260   IF STAGE > 3 THEN 290
270      GOSUB 1600                                    'TILLERING
280      GOTO  500
290   IF STAGE > 4 THEN 320
300      GOSUB 1700                                    'STEM EXTENTION
310      GOTO  500
320   IF STAGE >5  THEN 350                            'BOOTING
330      GOSUB 1800
340      GOTO  500
350   IF STAGE > 6 THEN 380
360      GOSUB 1900                                    'ANTHESIS
370      GOTO 500
380   IF STAGE > 7 THEN 410
390      GOSUB 2000                                    'GRAIN FILLING
400      GOTO 500
410   '  STAGE 8
420      GOSUB 2100                                    'RIPENING
430   '
500      GOSUB 12800                                   'ASSIMILATION
510      GOSUB 11500                                   'TRANSLOCATION
520      GOSUB 12000                                   'TOTALS
530      GOSUB 7000                                    'WRITE RESULTS
535   '  IF D=FINISH THEN GOSUB 14100                  'WRITE CARRY OVER FILE
540   NEXT  D
```

The new model is exceedingly user friendly and the results would appear as follows:

```
PUTU9 IRRIGATION SCHEDULING OF WHEAT
                                    Run date : 06-16-1987  Time : 15:26:39

LYSIMETER

        PLANT POPULATION            CULTIVAR       PLANTING DATE
          206  (/m^2)                 SST4           1 / 7 / 1984
        EXTENTION ENDED ON DOY  277

        SOIL DESCRIPTION:SANDY LOAM
        SOIL MOISTURE (mm/m)
        MAXIMUM        MINIMUM   INITIAL   EFFECTIVE ROOTING DEPTH
        200              76        200              1.8m

 1984

DOY   FH   LAI  IR RAIN PERC    WATER POTENTIAL      HU    Em    Ev    Es  Elys
                               S2   S3   ST   L
     (%)   x10  (%)     (mm)     (MPa*100)          (DD)      (mm*10)
Total rainfall in rest period= 0
GROWTH STAGE 3 - TILLERING PERIOD
183    0    0    0    0    0   -1   -1    0  -70     0    27     0    14     2

233   96    6    0    0  231   -1   -1   -2  -73    14    57     6     8    13
YRED=  6 TTRANS= 15 TPTRANS= 16 TLYS=  85 C=  623 BL/C=.46 GL/C=.00 SL/C=.26
DEEPERC= 231     TSOILVAP=  54   WUSE=  81    TAW= 209
 GROWTH STAGE 4 STEM EXTENTION PERIOD
234   96    6    0    0  231   -1   -1   -2  -73    15    60     6     8    22
235   96    8   26    0  238   -1   -1   -2  -74    16    59     6     7    45
276   98   85    0    0  249   -7  -17   -6  -88    40   112    99     6    45
YRED=  1 TTRANS=201 TPTRANS=207 TLYS= 199 C= 7888 BL/C=.61 GL/C=.00 SL/C=.10
DEEPERC= 249     TSOILVAP=  83   WUSE= 311    TAW= 114
 GROWTH STAGE 5 BOOTING
277   98   85    0    1  249   -8  -16   -7  -82    41    41    37     1    45

281   98   85    0    0  249  -11  -14  -10  -85    43    41    37     0    79
YRED=  1 TTRANS= 18 TPTRANS= 19 TLYS=  36 C= 8738 BL/C=.57 GL/C=.00 SL/C=.13
DEEPERC= 249     TSOILVAP=  83   WUSE= 330    TAW=  96   HT=.54
GROWTH STAGE 6 ANTHESIS
282   98   85    0    0  249  -12  -14  -11  -86    44    41    37     0    97

291   98   76    0    0  249  -11  -20  -14  -96    51    80    71     0    93
YRED=  1 TTRANS= 66 TPTRANS= 67 TLYS=  78 C=10958 BL/C=.45 GL/C=.19 SL/C=.11
DEEPERC= 249     TSOILVAP=  85   WUSE= 397    TAW=  64   HT=.64
GROWTH STAGE 7  GRAIN FILLING
292   98   76    0    0  249  -16  -23  -18 -106    52   109    96     0   112

326   27   10    0    0  249 -164 -164 -164 -279    81    88     0     0    13
YRED= 27 TTRANS=149 TPTRANS=287 TLYS= 220 C=15359 BL/C=.32 GL/C=.42 SL/C=.08
DEEPERC= 249     TSOILVAP=  86   WUSE= 547    TAW=   0
GROWTH STAGE 8 RIPENING
327   22   10    0    0  249 -164 -164 -164 -294    82   125     0     0    10
328   19    7    0    0  249 -164 -164 -164 -304    83   162     0     0    18

335   98    0    0    5  249  -41 -103  -25 -111    89    70    62     1     0
336   97    0    0    4  249  -51  -69  -40 -121    90    47    41     0     0
 Environmental potential yield for  1984    4547 kg/ha
TOTAL DEEP PERCOLATION    249 , EVAPORATION FROM THE SOIL  SURFACE   86   AND  TO
TAL WATER USE    561
```

S2, S3 and ST denote the second and third soil layers and total root zone respectively. L denotes leaf.

Running time on the SPERRY PC is approximately 20 minutes for a complete season. However, when compiled, this is reduced to less than five minutes. The IBM PC requires twice this length of time.

The complete coding of the programme for PUTU 9.86 is to be found in APPENDIX IV.

DOCUMENTATION

The wheat growing season is divided into a number of growth stages. These are illustrated in Fig. 3.3.

To promote the understanding of PUTU 9.86, to assist in the use of the model, and to facilitate future modification of the model a brief documentation of the system is here provided. This will be achieved by giving:

1. the location (line number) and titles of the subroutines. The titles, in fact, describe the operations performed by each subroutine, and

2. a description, together with source, of the parameters, functions and triggers included in the model.

The logistics of the computer programme may be studied by following the sequence of model operations here given. It is followed by a reference list whereby subroutines may be quickly found.

SEQUENCE OF OPERATIONS IN PUTU 9.86

	ESTABLISH PARAMETERS AND BOUNDARY CONDITIONS		
3100	PARAMETERS		
9500	ESTABLISH INITIAL CONDITIONS		
14000	COEFFICIENTS SOIL WATER EXTRACTION CURVE		
14245	ALTER INITIAL CONDITIONS		
	DATA		
10500	WEATHER DATA INPUT		
10800	HAIL		
14600	READ RAIN, IRRIGATION AND SPECIFIC DAYS TO RECORD		
14700	CREATE RAIN, IRRIGATION AND HAIL FILES		
	ENVIRONMENTAL VARIABLES		
8500	TEMPERATURE FUNCTIONS AND PROCEDURES		
9000	TOTAL EVAPORATION		
5500	ENVIRONMENTAL VARIABLES		
	TRIGGER AND EXECUTE APPROPRIATE GROWTH STAGE		
1400	STAGE 1	PRE-REST PERIOD	
1500	STAGE 2	REST PERIOD	
1600	STAGE 3	TILLERING PERIOD	
1700	STAGE 4	STEM EXTENSION	
1800	STAGE 5	BOOTING	
1900	STAGE 6	ANTHESIS	
2000	STAGE 7	GRAIN FILLING	
2100	STAGE 8	RIPENING	
6000	**WATER BALANCE**		
5700	CRITICAL LEAF WATER POTENTIAL		
13000	SIMULATE ROOT DEVELOPMENT		
8000	SOILWATER POTENTIAL FROM DESORPTION CURVE		
9800	SOILWATER CONTENT		
13300	SIMULATE SOIL-ROOT CONDUCTANCE AND LEAF WATER POTENTIAL		
13700	EXTRACT WATER FROM EACH LAYER		
2700	DISTRIBUTION OF INFILTRATED WATER		
	PRODUCTION		
10850	CROP HEIGHT	10900	LEAF GROWTH
11500	TRANSLOCATION OF ASSIMILATE		
12800	PHOTOSYNTHYSIS AND ASSIMILATION		
	RECORD RESULTS		
7000	RECORD RESULTS OF SIMULATIONS		
14095	RE-WRITE CARRY-FORWARD FILE		
	COMPUTATIONAL PROCEDURE ASSISTANCE		
2400	RESET	13900	DOY ON WHICH MONTHS END
2500	MEAN DATA	10000	SET VARIABLES TO ZERO
5000	TITLE PAGE	12000	SUB TOTALS
5300	TABLE HEADINGS	12500	MEANS
6500	DOY	11000	GEN ARTIFICIAL WEATHER DATA
15000	THE FUNCTIONS		

QUICK REFERENCE FOR FINDING SUBROUTINES

1000-	1400	STAGE 1	PRE-REST PERIOD
	1500	STAGE 2	REST PERIOD
	1600	STAGE 3	TILLERING PERIOD
	1700	STAGE 4	STEM EXTENSION
	1800	STAGE 5	BOOTING
	1900	STAGE 6	ANTHESIS
2000-	2000	STAGE 7	GRAIN FILLING
	2100	STAGE 8	RIPENING
	2400	RESET	
	2500	MEAN DATA	
	2700	DISTRIBUTION OF INFILTRATION WATER	
3000-	3100	PARAMETERS	
5000-	5000	TITLE PAGE	
	5300	TABLE HEADINGS	
	5500	ENVIRONMENTAL VARIABLES	
	5700	CRITICAL LEAF WATER POTENTIAL	
6000-	6000	WATER BALANCE	
	6500	DOY	
7000-	7000	RECORD RESULTS OF SIMULATIONS	
8000-	8000	SOILWATER POTENTIAL FROM DESORPTION CURVE	
	8500	TEMPERATURE FUNCTIONS AND PROCEDURES	
9000-	9000	TOTAL EVAPORATION	
	9500	ESTABLISH INITIAL CONDITIONS	
	9800	SOILWATER CONTENT	
10000-	10000	SET VARIABLES TO ZERO	
	10500	WEATHER DATA INPUT	
	10800	HAIL	
	10850	CROP HEIGHT	
	10900	LEAF GROWTH	
11000-	11000	GENERATE ARTIFICAL WEATHER DATA	
	11500	TRANSLOCATION OF ASSIMILATE	
12000-	12000	SUB TOTALS	
	12500	MEANS	
	12800	PHOTOSYNTHYSIS AND ASSIMILATION	
13000-	13000	SIMULATE ROOT DEVELOPMENT	
	13300	SIMULATE SOIL-ROOT CONDUCTANCE AND LEAF WATER POTENTIAL	
	13700	EXTRACT WATER FROM EACH LAYER	
	13900	DOY ON WHICH MONTHS END	
14000-	14000	SOIL WATER EXTRACTION CURVE COEFFICIENTS	
	14095	RE-WRITE CARRY-FORWARD FILE	
	14245	ALTER INITIAL CONDITIONS	
	14600	READ RAIN,IRRIGATION AND SPECIFIC DAYS TO RECORD	
	14700	CREATE RAIN,IRRIGATION AND HAIL FILES	
15000-	15000	THE FUNCTIONS	

PARAMETERS, TRIGGERS AND FUNCTIONS

The major parameters, phenological triggers and functions utilized in PUTU 9.86 constitute the essence of the model. They are now described.

Parameters

V01, V15, V16 The volumetric water content (mm/m) at soil water potentials of 10, 1500 and 1600 kPa respectively. 1600 kPa represents the lowest (driest) limit in soil water potential in the root zone, but not in the surface layer

W01, W15, W16 The layer water content (mm) at soil water potentials of 10, 1500 and 1600 kPa respectively.

PAW The layer plant available water (mm)

TPAW The profile available water content (mm)

SPL = 500 kg/ha. The specific leaf ratio

SEEDMAS = 0,03 g. The mass of a wheat seed

The units of heat accumulation above or below a basal temperature are growing degree days (DD) or cold units (CU) respectively.

BO = 8 °C. Basal temperature for calculating growing degree days.

HUMX = 20 °C. The daily maximum temperature for calculating growing degree days

CUC = 7,4 CU. Vernalisation requirements. The minimum cold units < 8°C required to end the tillering stage (see APPENDIX III)

CON1 = 21,8. Additional degree days per unit of cold unit deficit (DD/CU) (see APPENDIX III)

COO = 0,012. Constant for calculating respiration (Kaiser, 1976) (not required by this version of PUTU)

WEQ = 30 kg/(ha mm). Dry matter accumulation equivalent to water use (not used in this version of PUTU)

EFFMAX = 20%. The photosynthetic efficiency of utilization of PAR (Penman, 1971). PAR represents Photosynthetically Active Radiation in W/m^2 (not used in this version of PUTU)

FE = 68 * 10^(-9) kg/J. The photo-chemical equivalent (Penman, 1971) (not used in this version of PUTU)

RGR = 0,0182. Rate of vertical root penetration m/d (Botha, 1983)

AP = 2,1% The total roots found below 0,97 of the current rooting depth (see Chapter 4)

KSPO = -1,2 * 10^(-3) mm/(d kPa m pl). Maximum conductance of the root zone (defined in Chapter 4 and found by trial and error)

HUC = 145 DD critical heat requirement for transition from tillering to stem extension.

For convenience in future modelling, the parameters COO, WEQ, EFFMAX, and FE are retained here.

<u>Phenological triggers</u>

The various growth stages adopted for the wheat growth model are described in Fig. 3.3. They are defined as follows:

STAGE 1

JR is the DOY of commencement of the rest period. The pre-rest period is a dummy period stretching from January 1 to the day on which the rest period would hypothetically have occurred had there been a standing crop on January 1 of the first year of the data series.

STAGE 2 - THE REST PERIOD

JP is the day of the year on which planting occurred. It ends the rest period.

STAGE 3 - THE TILLERING PERIOD

Stage 3 ends when accumulated heat equals HUC. The latter is the critical heat (in DD) required to bring the specific cultivar from planting through tillering to the stem extension stage. It is adjusted according to vernalisation.

STAGE 4 - THE STEM EXTENSION PERIOD

Stem extension ends when DOY = ENDEXT. This ENDEXT is provided from field observations by the farm manager.

STAGE 5 - BOOTING

Booting ends when DOY = ENDBOOT = ENDEXT + 5.

STAGE 6 - ANTHESIS

Anthesis ends when DOY = ENDANT = ENDBOOT + 10.

STAGE 7 - GRAIN FILLING

Grain filling ends when DOY = ENDFILL = ENDANT + 35.

STAGE 8 - RIPENING

Physical maturity is reached when DOY = ENDRIPE = ENDFILL + 10.

<u>The functions</u>

FNDLENGTH - Maximum day length for each day of the year. It is an empirical function determined from LIST (1958)

FNMJD - Radiation at the top of the atmosphere. It is an empirical function determined from LIST (1958)

FNDLYR - Angström's formula for estimating daily incoming solar radiation from the fraction of possible sunshine hours

FN2 - An alternative to FN3

FN3 - Stomatal conduction as a function of leaf water potential. (Bristow, K.L., De Jager, J.M. and Van Zyl, W.H., 1981)

FN5 - Soil evaporation from the soil surface, Es

FN6 - The temperature limiting factor on photosynthesis

FN8 - The function S/(S+) in the Penman equation. It is a function of temperature (Schulze, 1975)

FN9 - Ratio of transpiration to maximum total evaporation. It is a function of leaf area index (originally Ritchie, 1972, changed to FN9 = 0,186.LAI ... Eqn 2.3 in Chapter 7)

FN10 - Priestley-Taylor formula (Priestley and Taylor, 1972)

FN12 - Construction respiration is equal to 0,5 of daytime photosynthesis (Kaiser, 1976)

FN13 - Night respiration as a function of nighttime temperature (Kaiser, 1976)

FN14 - Leaf area per unit plant development as a function of growing degree days (APPENDIX III)

FN15 - Exponential soil water extraction function (APPENDIX I)

FN16 - Calculation of leaf water potential using FN15

FN17 - Relative root development assumed to be a logistic function of days of the growing season

FN18 - The normalized natural logarithm of the relative volumetric soil water content for use in the computation of soil-root conductance (KSP line 13330). KSP, the soil-to-root conductance in a given layer is proportional to the square root of root mass and to the ratio of the natural logarithm of the current relative (to V16) volumetric water content divided by the natural logarithm of ratio of field capacity to volumetric permanent wilting point as computed by FN18 (Botha, 1983; Bennie and Botha, 1985).

The functions FNDLENGTH, FNMJD, FNDLYR, FN2, FN6, FN8, FN10, FN12, AND FN13 are not used in PUTU 9-86, but are retained for future reference.

<u>The yield function</u>

For irrigation scheduling the simplified yield model of Doorenbos and Kassam (1979) was included in PUTU. The relevant values of Ky are shown in Fig. 3.3. This means that the photosynthesis and translocation routines were not used in this particular application. The Doorenbos and Kassam (1979) yield model uses the concept of relative yield deficit, RYD, and relative evaporation deficit, RED. Thus, by definition

$$RYD = 1 - Y/Yo \quad \text{and}$$

$$RED = 1 - E/Em$$

The fundamental yield equation then reads:

$$RYD = ky\ RED$$

Hence,

$$Y = Yo - ky\ RED$$

For the ith growth stage $REDi = 1 - Ei/Emi$

For a season of n growth stages each having its own kyi

$$Y = Yo[1 - \sum_{i}^{n} kyi\ REDi \qquad ..(3.1)$$

PUTU 9.86, including Eqn 3.1, may be used to compute yield.

ADDITIONAL OPERATING INSTRUCTIONS

A simplistic weather generator (subroutine 1100) has been included for purposes of model development. It may be called by following the screen instructions.

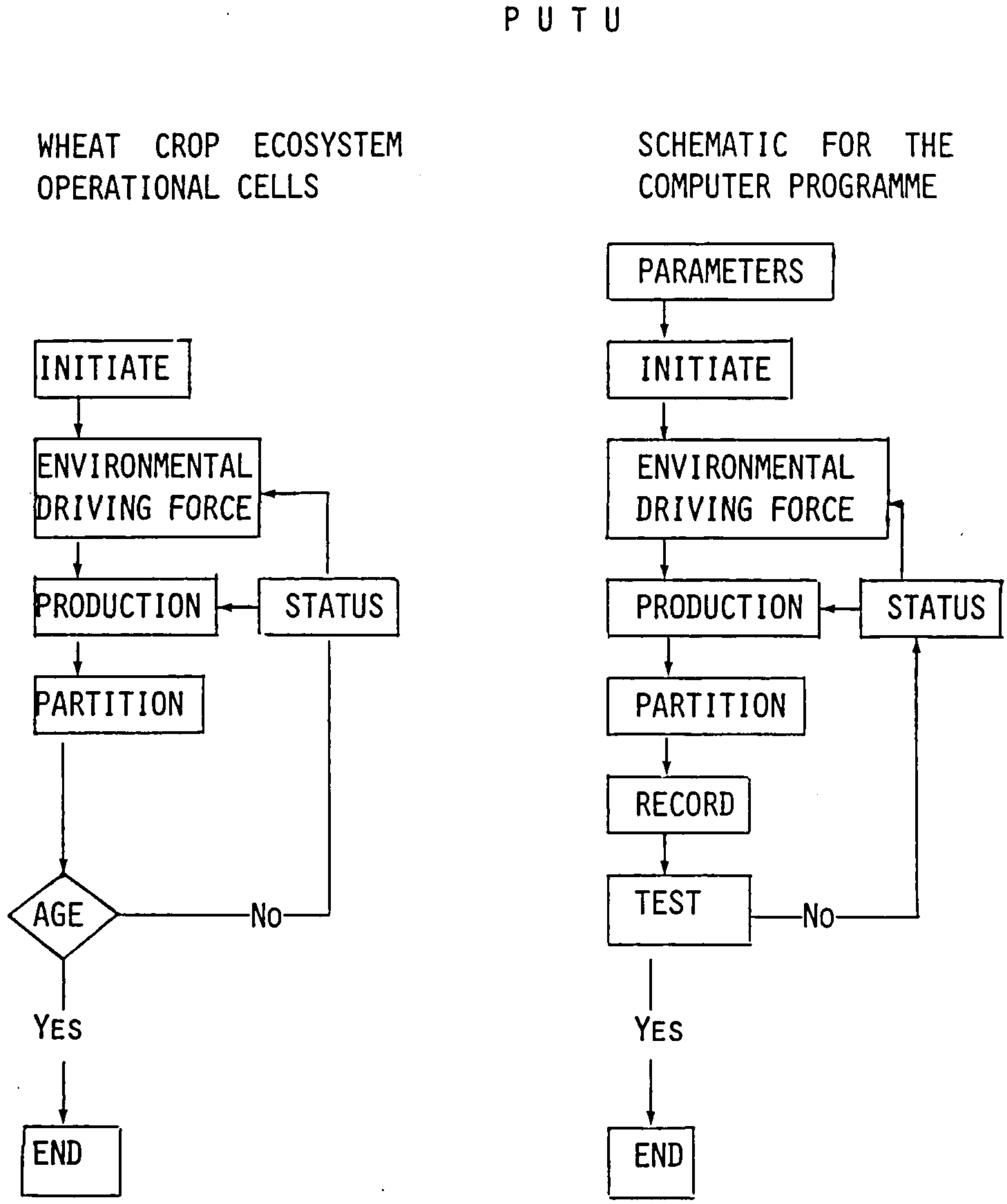
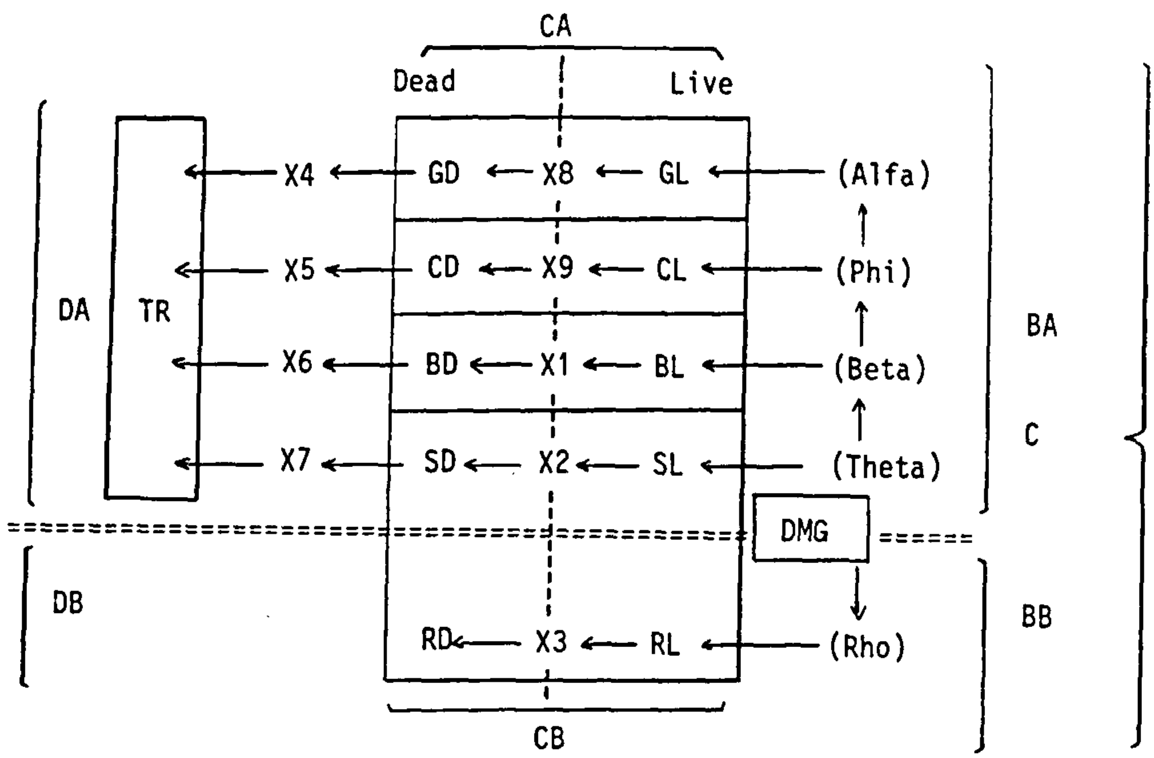


Fig. 3.1 - Schematic flow diagram which outlines the general structure of the computer programme for PUTU, the seasonal dynamic model of a wheat crop.



Symbol definition:

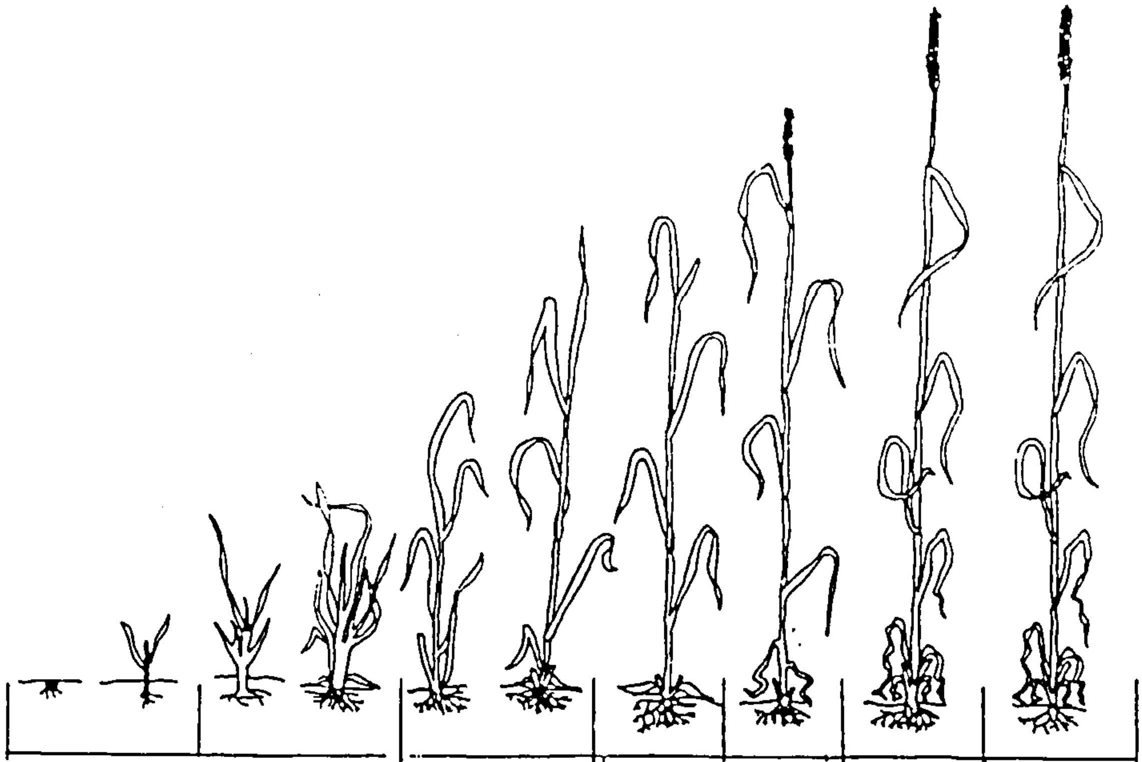
DMG = Daily dry matter assimilation (kg/(ha d))

GD = Dead grain
CD = Dead culms
BD = Dead leaves
SD = Dead stubble
RD = Dead Roots
TR = Senesced material
BA = Above ground live
BB = Beneath surface live
B = BA + BB
CB = Total beneath surface

GL = Live grain
CL = Live culms
BL = Live leaves
SL = Live stubble (Reserves)
RL = Live roots
DA = Above ground dead
DB = Beneath surface dead
D = CA + DB
CA = Total mass standing above surface
C = CA + CB

Alfa, Beta, Phi, Theta, Rho = Partitioning factors
X1, X2, ..., X9 = Dry matter coëfficients

Fig. 3.2 - Diagramatic presentation of the partitioning of photosynthate to the different plant components.



Stage	3	4	5	6	7	8
Description	Tillering	Stem Extention	Booting	Anthe= sis	Grain - filling	Ripening
Modified Zadoks Key	00 - 39	40 - 49	50-69	70-79	80-89	90-97
Ky	0,2	0,2	0,2	0,65	0,55	0,0
Trigger	ENDTIL : Hu=145	ENDEXT : OBSERVED	ENDBOOT : ENDEXT + 5	ENDANT : ENDBOOT + 10	ENDFILL : ENDANT + 35	ENDRIPE : ENDFILL + 10

Fig. 3.3 - Diagram depicting the growth stages utilized in PUTU 9.86, the corresponding Zadoks delimitation, the phenological criteria triggering progress to the next stage and Ky the wheat yield - relative evaporation deficit coefficient (Doorenbos and Kassam, 1979) applicable in each growth stage.

CHAPTER 4

THE ROOT DEVELOPMENT AND SOIL WATER EXTRACTION SUB-MODEL FOR WHEAT

INTRODUCTION

The accurate mathematical simulation of root development and water extraction from the soil root zone is a major problem confronting crop growth modellers. The PUTU 9 irrigation scheduling model used a simple double layered soil sub-model. It was deemed necessary to improve the reliability thereof by modelling a multi-layered root zone.

Improvements to PUTU 9 regarded as necessary, were:

(i) the inclusion of capillary flow upwards into the root zone from a wet substrate,

(ii) more accurate simulation of the influence of weather conditions upon the onset of plant water stress, and

(iii) the need to account for small increments in water which can only be accomplished using a multi-layered soil.

Recent scientific developments have made complex simulation feasible. Improved mathematics have reduced the computations required to manageable proportions. Relationships for describing the water desorption in soils have been refined by De Jong

(1983); Campbell and Campbell (1983); Mottram (1985); Schulze, Hutson and Cass (1985) and others. Furthermore, Botha (1983), Botha, Bennie and Burger, (1983) and Bennie and Botha (1985) have expressed the hydraulic conductance of the soil-plant system in terms of the rooting density and the soil water content.

The initial objective of this study was to simulate mathematically the root distribution and water extraction from a soil profile divided into a number of layers. It is important that routines for the simulation of vertical water movement by unsaturated capillary flow be added at some time in the future.

The major problem encountered was the simulation of the feedback mechanism operating in the soil-plant-atmosphere system when the crop is experiencing water stress. Mathematical analysis of such a feedback system requires the solution of one equation (D'Arcy's law) for two unknowns viz. leaf water potential, PSIl, and transpiration rate, T. A computer iteration technique for achieving this will be described. The theory was developed for a wheat crop, but has also been successfully extended to maize (De Jager, Mottram and Singels, 1986).

All line numbers quoted in the ensuing discussion refer to the listing of the programme for PUTU 9-86 in Appendix IV.

THEORY

Electrical analogue of the soil-plant hydraulic system

A simple electrical analogue and D'Arcy's law was adopted to model the soil-plant hydraulic process. For a layered soil the model is depicted in Fig. 4.1. Note particularly the diodes which prevent moisture flow from moist to dry soil layers via the root system. This was rather difficult to simulate. The resultant programming is found in lines 13715-13810 (see APPENDIX IV).

The model was originally developed for hourly time steps. It was subsequently found that a daily time step provided adequate accuracy. The development of the hourly model is described by De Jager and Singels (1986).

Symbol definition

The symbols used are the following:

A - root distribution exponent (/m),

Ap - percentage of roots found below the depth 0,97.ZEFFo (%),

DZRT - thickness of the individual soil layers (m),

DOG - day of the growing season,

DOY - day of the year,

Es - evaporation from the soil surface (mm/h), (SOILVAP)

K - hydraulic conductance (mm/(d kPa)),

KSPEFF - effective soil-root hydraulic conductance (mm/(h kPa)), k - hydraulic conductivity ((mm/d)/(m kPa)),

PSI - water potential (kPa),

PSIST - effective soil water potential (kPa),

RGR - vertical root growth rate (m/d)

R - root mass per unit of ground surface at soil depth z(kg/m^2),

RM - the total amount of root per unit surface area for the entire root zone down to depth ZEFF relative to the seasonal maximum value,

RPROPn - the proportion of roots per unit ground surface area found in the nth soil layer,

T - transpiration rate (mm/h),

V - volumetric soil water content (mm/m)

V01 - volumetric soil water content at 10 kPa (mm/m). Similarly V15, V16 and W01, W15 and W16 are values of V and W at 10, 1500 and 1600 kPa..

W - soil water content (mm)

ZEFF - current effective rooting depth (m)

ZEFFo - maximum effective root depth (m)

l - subscript denoting leaf,

N - there are N soil layers,

n - subscript denoting the nth soil layer,

o - subscript denoting the maximum value,

p - subscript denoting the total water pathway from soil into the roots and through the leaf surface,

s - subscript denoting soil, or, soil-root interface where conductance is concerned,

v - subscript denoting vegetation water pathway

x - subscript denoting xylem sap

z - depth in the soil measured positive downwards from the soil surface (m), The general mathematical expressions

The derivation of the equations describing the root distribution patterns are provided in Appendix I. In the model considered here, the symbol variable RM replaces the symbol x used in Appendix I.

Water flow through the soil-plant system is governed by D'Arcy's law, viz.

$$T = - k(\delta PSI/\delta z) \qquad \ldots(4.1)$$

Furthermore, the total plant transpiration rate is given by

$$T = \sum_{n=1}^{n=N} Tn \qquad \ldots(4.2)$$

where, the contribution to the total transpiration from the nth soil layer is given by

$$Tn = -Ksn \;.\; (PSIx - PSIsn) \qquad \ldots(4.3)$$

Eqn 4.3 is the appropriate form of D'Arcy's equation.

Water non-stress situations

Campbell and Campbell (1983) presented solutions of Eqn 4.1, in terms of resistances, for the case when no water stress exists. The solution here described will be undertaken in terms of conductances. The simple electrical circuit equations pertaining to the analogue illustrated in Fig. 4.1 were solved for water non-stress by assuming:

(a) that the conductance through the plant from root to leaf sub-stomatal cavity is infinitely larger than the conductance at the soil-root interface, and

(b) that all leaves in the crop are at approximately the same potential viz. PSIx = PSIl.

Under such conditions, the vegetation can, and does, accommodate atmospheric evaporative demand. Given the soil water potential in each soil layer; PSIl may now be found from

$$\text{PSIl} = \frac{\sum_{n=1}^{n=N} \text{Ksn.PSIsn} - \text{T}}{\sum_{n=1}^{n=N} \text{Ksn}} \qquad \ldots(4.4)$$

This may be written

$$\text{PSIl} = \text{PSIST} - \text{T/KSPEFF}$$

or

$$\text{T} = -\text{KSPEFF(PSIL} - \text{PSIST)} \qquad \ldots(4.5)$$

Here, KSPEFF and PSIST are defined as the effective soil hydraulic conductance and water potential respectively.

Hence, <u>the effective soil hydraulic conductance</u>, KSPEFF, is defined from Eqn 4.4. It is the algebraic sum of the hydraulic soil-root interface conductances in each soil layer. Thus,

$$\text{KSPEFF} = \sum_{n=1}^{n=N} \text{Ksn} \qquad \ldots(4.6)$$

Similarly, <u>the effective soil water potential</u>, PSIST, is defined from Eqn 4.4. It is the mean soil water potential obtained by weighting each layer's water potential according to its soil-plant hydraulic conductance. This PSIST offers an estimate of the soil water potential effectively sensed by the plant. Thus, for no water stress, (PSIST) is defined by

$$PSIST = \sum_{n=1}^{n=N} (Ksn \cdot PSIsn) / KSPEFF \qquad ...(4.7)$$

Eqn 4.5 is a form of D'Arcy's law and thus justifies the concepts and terminology for KSPEFF and PSIST.

In the simulation process PSIsn for each layer is estimated from the previous day's soil water status.

In the original PUTU 9 model of De Jager *et al.* (1982) PSIST was simply defined as the mean soil water potential over the entire root profile and the overall hydraulic conductance as

$$Kp = 1/(12,5 + [1 + 10\ EXP(-5(PSIST + 100))]$$

This function reflects the first assumption (viz. Kp = Ks). Furthermore the maximum conductance at the soil-root interface was then equal to 0,08 mm/(h bar) as determined by De Jager *et al.* (1982). Note that 0,08 = 1/12,5. It is thus apparent that soil-root conductance was assumed to decline exponentially with soil water potential, PSIsn, from an initial approximately constant value of 0,08 mm/(h bar). See the second term in the denominator.

Water stressed condition

In the water stressed condition, atmospheric evaporative demand requires (see Eqn 4.5) that PSIl must decrease to below its threshold value for normal transpiration. In nature water stress is evidenced by decreased stem elongation and leaf development and stomatal closure. Each of these symptoms is not necessarily initiated at the same given threshold leaf water potential (or soil water content) (see Ritchie, 1981).

Futhermore, a low soil water content induces resistance to water flow at the soil-root interface. This reduces Ks and also limits the flow of water through the system. Both phenomena decrease Kp with resultant decrease in PSIx (= PSIl). This, in turn, induces stomatal closure. This condition is simulated by decreasing T until D'Arcy's law is satisfied. The only manner in which PSIl and T can be found from Eqn 4.5 for this situation is by an iteration technique. Once the required steady-state PSIl, which is below threshold value, has been reached; leaf and stem (PSIx = PSIl) dehydration exist. These inhibit growth.

Root distribution and depth

The results of Chaudhary and Bhatnagar (1980) and Kmoch, Ramig, Fox and Kochler (1957), suggest that the distribution of wheat root mass (and hence water extraction) decreases exponentially with depth. Hence, an exponential model was postulated (see Fig. 4.1) for simulating the control of water extraction by root distribution. Such equation in terms of root length (L) is given by

$$L = Lo \, . \, EXP(-A \, . \, z) \qquad ...(4.8)$$

where Lo = the root length per unit area at the soil surface. Later root mass will be replaced by root length, but the same arguments will hold.

The proportion of roots per unit area of land surface within the nth soil layer, RPROPn, was derived (see Appendix I) from Eqn 4.8. It takes the form

$$RPROPn = EXP[- A \, . \, zn\text{-}1] - EXP[- A \, . \, zn] \qquad ...(4.9)$$

The constant A is a function of crop growth stage. It was evaluated by assuming that 2,7% (Ap = 2,7) of the roots are found beneath the rooting depth 0,97 ZEFF. This assumption was reached after examination of a number of wheat root distribution patterns. Its validity was verified by the goodness with which theoretical values agreed with measured values of RPROPn (see Table 4.1). Based upon this assumption, A may be evaluated using Eqn 4.10 in the manner described in Appendix I.

$$A = -(\ln 0{,}03) \, / \, 0{,}97 \, . \, ZEFF \qquad ...(4.10)$$

Originally, the rooting depth was modelled using regression equations found from the data reported by Botha, (1983). From this current effective rooting depth, ZEFF, was defined as

$$ZEFF = 0{,}0074 * DOG \qquad \text{for } DOG < 47 \qquad ...(4.11)$$

or

$$ZEFF = 0,0151 * DOG - 0,3282 \quad \text{for } DOG > 47 \qquad ...(4.12)$$

Later, in PUTU 9-86 however, a simplification, viz

$$ZEFF = RGR * DOG \qquad ...(4.13)$$

where RGR = 0,0182 m/d, was used (see Botha, 1983).

Accounting for a restricted root zone

Modeling root distribution and water extraction from a soil containing a layer impermeable to root or water penetration is difficult. Three possible assumptions, amongst others, are:

1. The root proportions and amounts in each layer assume the same values they would have had, had there been no restriction.

2. The root proportions in each layer remain the same as for the no-restriction case, but the total amount of roots which would have developed under no restriction is divided between the active layers.

3. The total amount of root developes as normal, but the root distribution pattern changes from an exponential to a cylindrical or semi-conal one.

PUTU 9.86 provides the computational steps for assumptions 1 and 2 (see lines 13167-13172). In the present study the model for assumption 1 was used.

Soil hydraulic conductance

The equation describing hydraulic conductance of the soil-root interface was taken from Botha (1983). It reads:

$$Ksn = 5{,}1065 * 10^{-6} + 0{,}7847 * 10^{-10} \ln(RDEN) * \ln(PSIsn/-47{,}7) \quad (mm/(h\ bar)) \qquad ...(4.14)$$

Where the root density in each layer, RDEN, is given by

$$RDEN = RPROPn \cdot LT(ZEFF) / DZRT \qquad ...(4.15)$$

LT(ZEFF) is the total root length per unit ground area in an entire root zone, currently of depth ZEFF. DZRT is the thickness of the soil layer. LT(ZEFF) was estimated following Botha et. al. (1983) using, for DOG > 10.

$$LT(ZEFF) = {,}806 - {,}2044\ DOG + 0{,}00645\ DOG^2 - 0{,}00003108\ DOG^3 \quad (km/m^2) \qquad ...(4.16)$$

Bennie and Botha (1985) modified Eqn 4.14 by placing soil-root hydraulic conductance directly proportional to the square root of rooting density and the natural logorithm of relative soil water depletion. The latter was expressed as the natural logarithm of the ratio between the current layer volumetric water content (Vn) and V16 (the volumetric water content at which PSIsn = -1600 kPa. i.e. permanent wilting point). This is a simple mathematical transformation of the initial results and does not represent a change in the fundamental theory. This principle, in a form which facilitates fine-tuning of the model, was then included in PUTU 9.86. Tuning the constant of proportionality was simplified by normalising the rooting density as well as the natural logarithm of relative soil water depletion terms. Normalization was achieved by replacing LT(ZEFF) by a hypothetical relative total "root mass", RM, normalized to a value of 100 at seasonal maximum root mass. The logistic expression assumed to reflect this relationship is given by FN17, viz.

$$RM = 100/(1 + EXP(-,06 \times (DOG - 50)) \qquad ..(4.17)$$

The relative volumetric water content was normalized using the multiplier ln[V01/V16], hence

$$FN18 = \ln(Vn/V16) / \ln(V01/V16) \qquad ..(4.18)$$

This yielded a final expression for soil hydraulic conductance in a given layer (see Line No 13330) of

$$Ksn = KSPEFFo \quad (RPROPn * RM) \quad / 10 \, . \, FN18 \qquad ..(4.19)$$

By trial and error it was found that the appropriate value of the maximum soil-root hydraulic conductance per unit soil thickness per plant was

$$KSPEFFo = -1,2 \quad \times 10 \quad mm/(d\ kPa\ m\ pl).$$

Extraction of water from the multi-layered soil

The initial wheat model PUTU 9 utilized a double layered root zone. It became evident however, that a multi-layered root zone was required to improve simulation of water dynamics in the system. The original double layered model had evolved from a model developed by Mallett and De Jager (1974). The double layered model is reliable for large rainfall amounts and irrigations (see Van Zyl, De Jager and Van Rooyen, 1981). The influence of water quantities smaller than say 20 mm/d however, becomes lost in the large volume of soil found in the second layer during the latter part of the season. Hence the decision to introduce a nine-layered root zone into PUTU 9. A layer thickness of 0,15 m meant that available water in a soil layer amounted to approximately 15 mm. Hence water changes greater than approximately 5 mm (30% of that available) were now accurately accounted for. As daily transpiration, at crop maturity generally exceeds this value, the error inherent in the model was expected to be less than one day per wetting event. Improving accuracy at the expense of computing time is possible by the simple introduction of layers thinner than 0,15m. A diagrammatic presentation of the new root sub-model is given in Fig. 4.1.

The new water extraction sub-model essentially simulates roots which penetrate linearly with respect to time. The root mass is exponentially distributed throughout the entire root zone at any time.

Total root mass per unit surface area (expressed in relative units 0-100) was assumed to change as a logistic function of time (see Eqn 4.17).

The model first determines the effective soil water potential, PSIST, for the entire root profile. This is the mean, over all the soil layers, of the water potential in each layer weighted according to current root-soil conductance . The leaf water potential and transpiration rate are then computed by iteration using Eqn 4.5 and the root-to-soil conductance in each layer. The latter, expressed as a function of the square root of root mass and the natural logarithm of the ratio of current relative volumetric water contents in each layer was computed using Eqn 4.19. The new version of PUTU for wheat which includes these routines is entitled PUTU 9-86. They are listed in detail in APPENDIX III. Since the basic structure of PUTU 9-86 has already been described in Chapter 3; the computation of only the leaf water potential and soil water extraction will be outlined here.

The soil water desorption curve

A model for soil water potential in terms of soil water content was sought. The model of Campbell and Campbell (1983) was computerised (SOILCHR). De Jong (1982) produced a similar model based upon the well known Clapp and Hornberger (1978) equations. Schulze, Hutson and Cass (1985) report empirical equations in terms of clay content based upon unpublished results of Hutson. Mottram (1985) reports similar equations. Similar equations reported by Burger, Bennie, Botha and Du Preez (1979) apply mainly to sandy soils however.

While the spline function of the original PUTU9 functioned satisfactorily, it was decided to streamline the computations. The Hutson equations were used to determine soil water contents corresponding to soil water potentials of 30 kPa (V30) and 500 kPa (V50) and fit a curve through these two points. A detailed description of this procedure is given in Appendix I. The curve so obtained was used as the soil water extraction curve. Since the plant commences experiencing resistance to water flow when layer soil water potential lies somewhere between these two values, accuracy is required in this region. Utilizing this procedure the soil water contents at maximum (V01), minimum (V15), permanent wilting (V16) and profile available water (TPAW) could be calculated. Accuracy was within approximately 5 mm/m (5% on 100 mm/m). This was deemed accurate enough for the purpose at hand. The elementary mathematics involved in, and results derived from, this model are given in APPENDIX I and APPENDIX II respectively.

SEQUENCE OF OPERATIONS FOR COMPUTING EXTRACTION OF WATER FROM EACH LAYER OF THE MULTI-LAYERED SOIL

In the computer programme the individual soil layers are denoted L.

INITIAL CONDITIONS

Establish for the entire run

Line #	
9556	Layer thickness DZRT (m) Root-soil conductance coefficient -1,2 x 10 mm/(d kPa m pl)
9590	Maximum effective rooting depth ZEFFO (m)

Now calculate for each layer :

9591-9594	Initial water content V(L) (mm/m), W(L) (mm)
3130-3137	Soil water extraction coefficients M(L), PO(L)
3139-3147	Wilting point V15(L) (mm/m), W15(L) (mm)
	Field capacities V01(L) (mm/m), WO1(L) (mm)

DAILY STATUS AND ENVIRONMENTAL VARIABLES

Calculate for each day:

8000-8040	Soil water potential in each layer PSIS(L) (kPa)
9090-9120	Evaporation from soil surface SOILVAP (mm)
2840-2890	Runoff and infiltration RUNOF (mm) INFIL (mm)
2910-3090	Rainfall and/or irrigation water recharge in each layer (mm)
1300-13040	Current rooting depth ZEFF (m)
13050-13172	Proportion of roots in each soil layer RPROP(L)
13160-13166	Relative total root length per unit surface area in entire current rooting depth RM - assumed a logistic function of days since planting, DOG
13167	Number of layers, DZRT thick, into which roots have penetrated NOLAY
13320	Root proportion in each layer RPROP(L)

13330	Root-soil conductance of each layer KSP(L) (mm/(d kPa layer))
13340	Effective root-soil conductance of entire soil profile KSPEFF (mm/(d kPa))
13380	Effective soil water potential for entire soil profile PSIST (kPa)

ITERATION ROUTINE

13380-13680	Iterate for crop mean leaf water potential, PSIL, and transpiration rate, T

WATER EXTRACTION ROUTINE

13700-13810	Extract water (transpiration) from each soil layer TS(L) (mm/layer)
13830-13880	Calculate new water content V(L) (mm/m) and W(L) (m) in each layer

Procedure for the preliminary validation

Root distribution

The assumption expressed by Eqn 4.10 was tested against the data reported by Botha (1983). He seeded Zaragoza wheat at the rate of 80 kg/ha in rows 300 mm apart. The soil was an Annandale series in which an orthic A-horizon overlies a yellowish brown apedal B-horizon of eolian sand. Three treatments were applied:

TREATMENT I -	Conventional 250 mm mouldboard ploughing,
TREATMENT II -	250 mm mouldboard ploughing followed by 500 mm deep ripping, and
TREATMENT III -	Same as Treatment II but the traffic zones were loosened by deep ripping after planting.

Root length density was determined in soil plots of area 10 m^2. Samples were taken down to 2 m depth at two weekly intervals in each treatment.

Simulated values of the root proportions in each layer obtained using Eqn 4.9 (A found from Eqn 4.10) and the known effective rooting depth (2 m) on given days were compared with the corresponding measured values. The results are shown in Table 4.1 and 4.2.

<u>Water extraction</u>

The parameter values in Eqn 4.11 through 4.16 pertain to soil of the Annandale series as found on the Vaalharts Irrigation Scheme. It is dangerous to extrapolate such results to other circumstances. As a preliminary test of the theory however, it was deemed expeditious to investigate how accurately this model would simulate water extraction from a Bainsvlei series, because test data and a modified (Singels, 1984) multi-layered version of PUTU 9 were already available.

This model computed the daily water balance by extracting daily transpirative losses from the water in each soil layer. Computed water contents were compared with field gravimetric measurements made in dryland wheat. The data were collected by Singels (1984) at Baunton on a Bainsvlei series which was 1,5 m deep and at

Hopefield on a Bainsvlei series 2 m deep. These data were appropriate as water stress had occurred during the seasons investigated. Weather input data for the calculations were obtained from the Soils and Irrigation Research Institute. The results are reported in Table 4.3.

The iteration approach for solving for PSIl and T under stressed conditions was tested in the Singels (1984) multi-layered soil model. It incorporates Equations 4.5, 4.6, 4.7, 4.9, 4.10, 4.11, 4.12, 4.14, 4.15 and 4.16.

Occasionally the predicted values of PSIl were higher than the PSIsn in, say, the nth layer. This would cause water to flow from other soil layers to the leaf and then to the dry soil layer. While this is possible in an electrical network it is not biologically feasible. Hence, statements eliminating such flow from the computation were included. Such procedure is represented by the diodes shown in Fig. 4.1 and simulated by lines 13760-13820 in the computer programme. It was subsequently found that the model performed minimally better without this routine. Hence it was circumvented for the present application. It is still available for future use when needed.

RESULTS AND DISCUSSION

The root distribution model described by Eqn 4.9 accurately simulated the proportion of roots in the different soil layers (see Table 4.2). It is evident that the assumption described by Eqn 4.10 is valid for the particular set of conditions investigated. It deserves however to be stressed that it is an extremely dangerous practice to extrapolate results obtained in one soil type and for a single depth to other conditions. Unfortunately measurements for only a 2m rooting depth were available. Furthermore, while all the simulation indices, SI (after Willmott, 1982), indicated acceptable reliability (SI > 0,8), the model appeared to be more accurate for the Treatments II and III than for the conventional ploughing Treatment I. Results for other rooting depths and other soil types should be undertaken to prove the general reliability of the model. Should this relationship be verifiable for other effective rooting depths, and for the soil types found around Hartswater, it will provide a simple model for root development as the only input required for Eqn 4.9, 4.10 and 4.16 are the day of the growing season (DOG) and an estimate of the effective rooting depth.

Results of tests on the accuracy of simulation of layered soil water contents are presented in Table 4.3. These results did not conclusively validate the mathematical expressions utilized for hydraulic conductance. The slopes and intercepts differ too greatly from unity and zero respectively. The r^2 and SI however, are sufficiently high (r^2 > 0,6 and SI > 0,7) to suggest that the technique had scientific merit and deserved further investigation. It was evident, from the rapid depletion of soil water in each layer, that Eqn 4.14 over estimated the hydraulic conductance in each layer. The soil-plant hydraulic conductance of the entire wheat crop can be as high as 0,08 mm/(h bar) (De Jager, et. al., 1982). The conductances predicted by Eqn 4.14 reached 0,05 mm/(h bar) in an individual, 150 mm thick, layer. This seems disproportionately high and could explain the excessively rapid water extraction from wet, densely rooted layers. This problem was later overcome by using the root development equation, Eqn 4.13 and the Bennie and Botha (1983) conductance relationship LINE 13330 (see APPENDIX IV).

The SI and r^2 obtained however, were superior to those found by Singels (pers com) and De Jager, et al. (1982) - the first for a non-iterative multi-layered model and the second for a non-iterative double layered soil. Hence, the iteration procedure and these equations were deemed to have improved the accuracy of simulation of water extraction from individual soil layers and the onset of water stress conditions. Considering that the equations were applicable to an Annandale series, these preliminary tests were stringent. Use of parameters applicable to Bainsvlei series could only improve the degree of compatability.

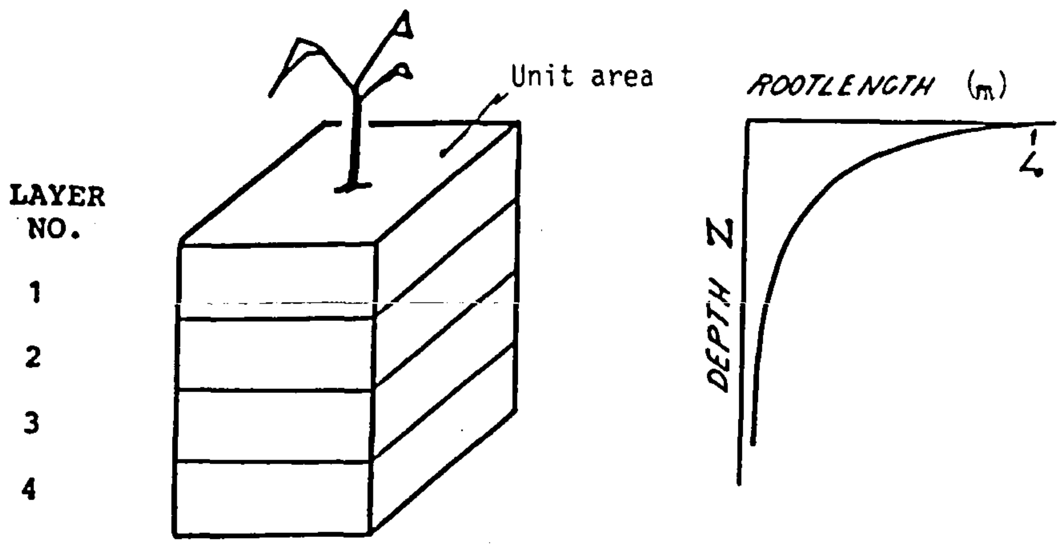
CONCLUSIONS OF PRELIMINARY VALIDATION

For an Annandale series soil at Vaalharts, in which the wheat roots had penetrated to depths of approximately 2 m, root distribution was successfully simulated by assuming that root length decreased exponentially with depth. The constant in the exponent was evaluated by assuming that 2,7 % of the total roots were found below 0,97 of the current rooting depth.

The theory and computational procedures for solving the electrical analogue equations describing water extraction from a multi-layered soil profile by iteration were developed.

The exponential root distribution model and the hydraulic conductance iterative model were reasonably successful in simulating daily soil water content under dryland wheat throughout two different growing seasons on two independent farms.

The functions used appeared to have over estimated soil hydraulic conductance. Further refinement of the relevant equations was required. The iterative approach to modelling a multi-layered root profile had however demonstrated sufficient simulation prowess to warrant further development and inclusion in the irrigation scheduling model. These modifications (Eqn 4.17, 4.18 and 4.19) were introduced and the model tested on data collected in 1984 and 1985.



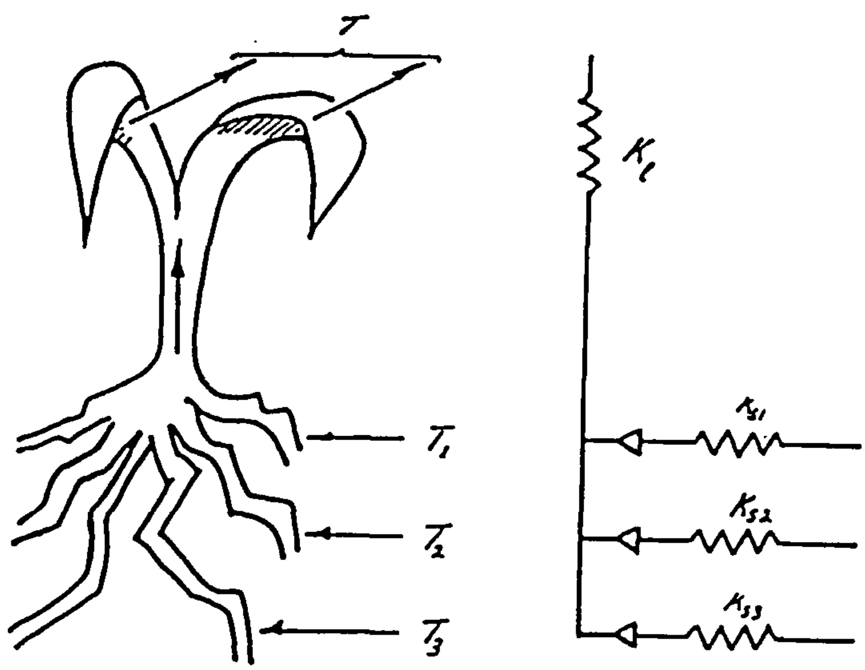


FIG. 4.1 - Diagrammatic representation of the multi-layered root zone model and its electrical analogue.

TABLE 4.1 - Measured (Botha, 1983) and simulated values of the proportion of the total roots found in each soil layer, RPROPn.

DATE	LAYER	TREATMENT 1 MEASURED	TREATMENT 2 MEASURED	TREATMENT 3 MEASURED	SIMULATED
	mm				
DOY 79	150	,36	,29	,32	,33
	300	,30	,22	,20	,22
	450	,19	,14	,16	,15
	600	,08	,11	,12	,10
	750	,00	,18	,15	,12
	900	,06	,03	,02	,05
	1050	,02	,02	,02	,03
DOY 93	150	,24	,38	,26	,33
	300	,19	,28	,19	,22
	450	,12	,14	,17	,15
	600	,13	,10	,12	,10
	750	,24	,08	,13	,12
	900	,05	,02	,10	,05
	1050	,03	,01	,03	,03
DOY 113	150	,24	,26	,35	,33
	300	,16	,23	,22	,22
	450	,17	,23	,16	,15
	600	,15	,09	,11	,10
	750	,14	,11	,12	,12
	900	,11	,06	,04	,05
	1050	,03	,03	,01	,03

TABLE 4.2 - Coefficients of determination (r^2), mean absolute differences (MAD), simulation indices (SI), slopes and intercepts for the comparison of simulated fractions of total roots found in the different soil layers, RPROPn, to the measured values. The latter were obtained from Botha et al (1983). The root depth was approximately 2 m in all cases. SI was determined according to Willmott (1982).

TREATMENT	DAY	SLOPE	INTERCEPT	r^2	MAD	SIMULATION INDEX (SI)
1	79	,73	,03	,93	,04	,96
1	93	,94	,01	,61	,04	,87
1	113	1,42	-,06	,79	,04	,89
2	79	1,00	,00	,91	,02	,98
2	93	,74	,04	,97	,03	,97
2	113	1,03	,00	,84	,03	,95
3	79	,97	,00	,95	,02	,99
3	93	1,40	-,06	,94	,03	,96
3	113	,89	,02	,99	,01	,99

TABLE 4.3 - Test of accuracy of the simulation of soil water content in each soil layer at Baunton and Hopefield. Slope and intercept of the linear regression are given with coefficients of determination (r^2) and Simulation Index (SI) after Willmott (1982).

LOCATION	SOIL LAYER	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	r^2	SIMULATION INDEX (SI)
	(mm)		(mm/m^2)			
BAUNTON	0-150	0,53	63	,79	,62	,71
	150-400	1,00	19	,69	,47	,66
	400-650	1,11	-23	,78	,61	,83
	650-900	1,47	-45	,91	,82	,88
HOPEFIELD	0-150	0,56	26	,69	,48	,81
	150-360	0,70	25	,81	,65	,88
	360-575	0,79	19	,74	,55	,86
	575-790	0,95	3	,84	,70	,91
	790-1000	0,90	6	,87	,76	,92

CHAPTER 5

MICROMETEOROLOGICAL METHODS FOR ESTIMATING EVAPOTRANSPIRATION

INTRODUCTION

The reliability of the PUTU 9.86 irrigation scheduling model is totally dependant upon the Penman-Monteith equation (Thom, 1975) for estimating total evaporation. It is therefore imperative that its accuracy be verified. This was done during 1985 using a full set of micrometeorological observations. Later as reported in chapter 7 it was shown that the Penman-Monteith adapted for use with data from the automatic weather station also provided accurate estimates of total evaporation. The influence of atmospheric stability was also investigated. The Bowen ratio energy budget method (Thom, 1975) and the iteration technique (De Jager et al, 1982) and (Bristow et al, 1982) for estimating evapotranspiration were also verified.

THE MODIFIED PENMAN-MONTEITH EQUATION

List of symbols

Em	:	Maximum total evaporation (mm/h)
u	:	wind speed (m/s)
s	:	Slope of the saturated vapour pressure temperature curve (Pa/°C)
γ	:	Thermodynamic value of the psychrometric constant (Pa/°C)
Qn	:	Net radiation (W/m^2)
G	:	Soil heat flux density (W/m^2)
ρa	:	Air density (kg/m^3)
Cp	:	Specific heat of air (J/(kg °C)
ϕa	:	Aerodynamic conductance of the atmosphere (m/s)
δe	:	Difference between the saturated vapour pressure and vapour pressure of air at a specific temperature (mbar)
L	:	Latent heat of evaporation of water (J/kg)
ϕs	:	Conductance for water vapour exchange through the surface of a whole wheat crop (=0,03 m/s see Russell (1980))
ra	:	Aerodynamic resistance of the atmosphere (s/m)
z	:	Height above ground level at which measurements were made (m)
d	:	Zero plane displacement level (m)
zo	:	Roughness parameter
k	:	Von Karman's constant (0,41)
u*	:	Friction velocity (m/s)
Φm	:	Stability function
Ri	:	Richardson number
g	:	Gravitational acceleration (m/s^2)
$\overline{T}$	:	Average air temperature (°K)

The Penman-Monteith equation (Thom, 1975) for estimating maximum total evaporation in mm/h is given by

$$Em = 3600 \ [s(Qn-G)/(s+\gamma*) + (Cp\delta e\phi a)/(s+\gamma*)]/L \quad ..(5.1)$$

where 3600 ensures the coherency of units, and

$$\gamma* = (1+\phi a/\phi s) \quad ..(5.2)$$

From Thom, (1975), the generalized expression for the wind-profile relationship is

$$du/dz = [u*/k(z-d)]\Phi m \quad ..(5.3)$$

Here the stability function, Φm, is greater or less than unity depending upon the stability conditions existing in the atmosphere.

Aerodynamic resistance (ra) for neutral conditions ($\Phi m=1$) is derived from Eqn 5.3. Thus

$ra = [\ \ln (z-d)/zo)]^2 /k^2u$ which may be substituted in

$$\phi a = 1/ra \quad ..(5.4)$$

It can be shown, following the same argument as Thom (1975) that

$$\phi a = 1/(ra\Phi m^2) \quad ..(5.5)$$

For stable conditions Webb (1970), Munn (1966) and Lumley and Panofsky (1964) developed the relationship

$$\Phi m = (1-5Ri)^{-1} \quad ....Ri > 0 \qquad ..(5.6)$$

While, for unstable conditions, Dyer and Hicks (1970) and Businger (1966) proposed

$$\Phi m = (1-16Ri)^{-0,25} \quad ....Ri < 0 \qquad ..(5.7)$$

where, the Richardson number is given by

$$Ri = g/T(dT/dz) \; / \; (du/dz)^{2} \qquad ..(5.8)$$

Initially, the objective of the study was to estimate Em from Eqn 5.1 utilizing first Eqn 5.4 and then Eqn 5.5 and to compare these estimates separately with hourly lysimeter observations, so as to evaluate the effects of stability upon Eqn 5.1.

Materials and methods

The study was carried out on the experimental plot at the West Campus of the University of the Orange Free State. Hourly measurements of Em from irrigated spring wheat were obtained from a 50 t, $10m^2$ lysimeter surrounded by 4 ha of wheat. Hourly estimates of Em were calculated from Eqn 5.1 using the following measurements made in the wheat field.

- net radiation from a Middleton 970 net radiometer installed 1,5m above ground level,

- soil heat flux density from three soil heat flux sensors imbedded 5mm below ground level,

- wind speed using a Gill three cup anemometer installed 1,5m above ground level, and

- wet and dry bulb temperatures from an aspirated psychrometer installed 1,5m above ground level.

The stability function was calculated from Eqn 5.6, 5.7 and 5.8 using the following:

- wind speeds at 0,7 and 2,0m above an adjacent grass site, and

- air temperatures at 0,7m and 2,0m above grass level.

Sixty three values (N) under varying weather conditions were used for the comparisons. The wheat crop had a leaf area index greater than 3. The entire area under wheat including the lysimeter and the grass site were supplied with adequate water to prevent moisture stress. Thus evaporation from the crop proceeded at the maximum rate at all times during the experiment. Standard statistical comparisons plus the simulation index, SI, described by Willmott (1982) were applied. Hourly Em estimated from Eqn 5.1, not adjusted for atmospheric stability (i.e. using Eqn 5.4), were compared to lysimeter values. In addition, hourly Em estimates from Eqn 5.1 adjusted for atmospheric stability using Eqn 5.5 and Φm, computed from either Eqn 5.6 or Eqn 5.7, were compared against measured evaporation.

Results and discussion

Table 5.1 presents a summary of the frequency distribution of the Φm values. The stability function differed from unity by more than 10% in 51% (32 observations) of the cases. The case $0,60 < \Phi m <= 0,80$ i.e. $(0,36 < \Phi m^2 <= 0,64)$ occurred in 8 out of 63 events (13%). This implies that the adjustments to Φm lay between 64% and 36% in 13% of the cases. This range and distribution was deemed adequately varied to stringently test the stability theory.

Fig.5.1 and 5.2 compare Em measured with Em estimated for $\Phi m = 1$, and for $\Phi m \neq 1$ respectively. Table 5.2 is a summary of the hourly relationship between Em measured and Em estimated, according to the two methods.

It is evident that the Penman-Monteith equation unadjusted for atmospheric stability provided accurate estimates of hourly Em. A mean difference of 0,03 mm/h and simulation index of 0,97 is highly acceptable for practical irrigation scheduling. An error of 0,03 mm/h is half the error that could be tolerated when keeping an accurate daily soil water budget.

No improved accuracy was obtained when the Penman-Monteith equation was adjusted for atmospheric stability. The index of agreement is marginally worse at 0,94 as compared to 0,97. The mean absolute difference of 0,10 mm/h is also minutely worse.

Conclusion

The Penman-Monteith equation was used to compute hourly evaporation. The mean absolute difference between measured and computed values was 0,09 mm/h in the range of atmospheric stabilities $0,6 < \phi_m < 1.8$. Estimates of maximum evaporation rate from for wheat obtained from the Penman-Monteith equation, will not be improved by adjusting it for atmospheric stability.

Similar good agreement was attained with daily estimates. The mean absolute difference between measured and calculated values was 0,5 mm/d. Here, correcting for atmospheric stability did produce improvement.

ESTIMATION OF NET RADIATION MINUS SOIL HEAT FLUX FROM TOTAL SOLAR RADIATION

An important relationship utilized in the Penman-Monteith equation, when automatic weather stations are used, is that for estimating net radiation minus soil heat flux (Qn - G) from incoming total solar radiation. This relationship is necessary as it is not possible to measure net radiation on a continuous basis using an automatic weather station. The relationship found by De Jager <u>et al</u> (1982) was re-determined (Eqn 5.9) using measurements made during 1985. The goodness of fit is reported in Table 5.4. The then existing relationship was replaced by this new function. It reads:

$$(Q_n - G) = 0,75\ S_t - 72\ W/m^2 \qquad ..(5.9)$$

DAILY VALUES

Putu 9.86 requires daily values of evaporation. It was necessary to check whether the daily values from the Penman-Monteith equation were as accurate as the hourly values have been shown to be.

The results reported in Table 5.3 verify that this is in fact so. Hourly values were calculated using Eqn 5.1 and the micrometeorological data. These hourly values were then integrated over the daylight period and the necessary comparisons carried out.

It is apparent from Fig 5.1 that correcting for atmospheric stability minutely improved the accuracy of estimate. This is not reflected in Table 5.3 however. The low absolute difference between measured and estimated values (0,5 mm/d) is however, highly acceptable for accurate irrigation scheduling.

ASSUMPTION CONCERNING WIND MEASUREMENT, CROP HEIGHT, AND AERODYNAMIC CONDUCTANCE

The height of the anemometer on the automatic weather station was 3.15m. Hence, using these data implies that wind speed at this height above neighbouring short grass approximates the wind speed at the same height above the wheat crop. In Chapter 7 it will be shown that automatic weather station data may successfully be used in the Penman-Monteith equation. And it may thus be concluded that the above is a workable assumption. Certain comments regarding the effect of measurement height are appropriate at this stage however.

The Penman-Monteith equation as utilized in PUTU 9 and PUTU 9.86 uses aerodynamic conductance to account for the influence of wind upon crop total evaporation. The form of this equation is

$$F(u) = \phi a = k^2 u/[\ln((3.15-d)/zo)]^2 \qquad ..(5.10)$$

where,

k is von Karman's constant, and d and zo are the zero plane displacement and roughness heights respectively.

Aerodynamic conductance, ϕa, corresponds to the wind function of the Penman equation F(u). The strong dependence of the aerodynamic conductance, as computed in this application upon zero displacement height is clearly evident from Eqn 5.10. The present procedure assumed d to be a constant fraction (0,63) of crop height. Hence as the wheat crop developed, d increased, thereby effectively increasing aerodynamic conductance as z is the unchanging height of the anemometer on the automatic weather station. This situation caused a marked increase in simulated crop evaporation. For example, on windy days with a crop height of 0,7 m, crop total evaporation computed using Eqn. 5.1 could exceed computed reference evaporation by as much as 5 mm/d. Such arte fac would markedly influence the soil water budget.

The sensitivity of aerodynamic conductance calculated using the assumption regarding wind regime above wheat and short grass are clearly illustrated in Fig. 5.3. The latter exaggerates the situation because it shows results for a measurement height of 2 m whereas the automatic station anemometer height was 3.15m. The results however do support the alternative argument for the use of Er (d constant at 0.0315 m) instead of Em computed with crop height increasing with time. Use of Er embraces the assumption that the wind speed at the same distance above wheat crop and short grass surfaces are more nearly equal than are those resulting from the initial assumption.

The desire to account for crop architecture is the motivation for using Em. It was hoped that this step would eliminate some of the anomalies generally found in the use of crop coefficients. Irrespective of whether Em or Er are used with the automatic station data; it is apparent the the anemometer should be installed as high as possible, but not so high as to completely outride the influence of the boundary layer.

THE BOWEN METHOD AND THE ITERATION TECHNIQUE

Two alternatives to the Penman-Monteith equation for estimating crop total evaporation are available. They are the Bowen ratio energy budget method (Bowen) and the iteration technique (Iter). The former is a standard micrometeorological technique (Thom, 1975). The micrometeorological iteration technique has been fully described by De Jager <u>et al</u> (1982) and Bristow and De Jager (1982).

During 1985 hourly micrometeorological investigations were undertaken to estimate evapotranspiration utilizing the Bowen technique. Measurements were carried out from DOY 261 onwards at a stage when the leaf area index was greater than 5.

Inter-comparisons between these estimates and measurements from the lysimeter are reported in Table 5.5. The results indicated a relatively high correlation coefficient, especially when daily values are considered. The two methods however under-estimate evapotranspiration to a large extent. This is possibly attributable to the small vertical gradients in the meteorological elements observed (see Table 5.6). The slopes of 0,97 and 0,91 (together with high correlation coefficients) for temperature and relative humidity, respectively, are indicative of low vertical gradients. In order to try and explain the poor Elys/Iter agreement in 1985; the comparisons were repeated, but with assuming that the relative humidity at the momentum exchange level was 10% higher than that at 2m height. These comparisons between the iteration technique (Itera - Table 5.5) and the lysimeter reflected a decrease in the correlation coefficient, but an improved simulation index. It was therefore suggested that the relative humidity at the effective crop surface (Rho) was actually higher than what was measured at the momentum exchange level. A high difference (Rho-Rhr) in relative humidity would have resulted in a better estimation of E in 1985 using the iteration technique. Rhr is the relative humidity at a 2m high reference level. On the other hand, the careful tests conducted in 1986 confirmed the accuracy of the original iteration techniques (Bristow and de Jager 1982). Measurement error could probably explain the poor agreement of 1985.

Good agreement was obtained between the Bowen ratio method and the iteration technique (Table 5.5).

The canopy surface temperature estimated using the iteration technique (TO-iter) compares favourably with values measured utilizing an aspirated psychrometer (TOMES) installed at the momentum exchange level within the wheat and an infra-red thermometer (IRT) (see Table 5.7).

It is evident from these results that none of the highly complex techniques described approach the accuracy of the Penman-Monteith equation. However, neither the iteration technique nor the Bowen ratio method should be viewed over critically on this evidence. The iteration technique can be greatly simplified using relationships of the type reported in Table 5.6. Futhermore, iterating for relative humidity at the momentum exchange level (Rho) rather than canopy temperature (Tempo) would greatly simplify the procedure. The need to measure Rho - always a difficult matter, would be eliminated. This could indeed make the iteration method an attractive alternative. The high simulation index obtained from comparisons between the Bowen and iteration techniques is indeed interesting and suggest that the iteration technique deserves further investigation.

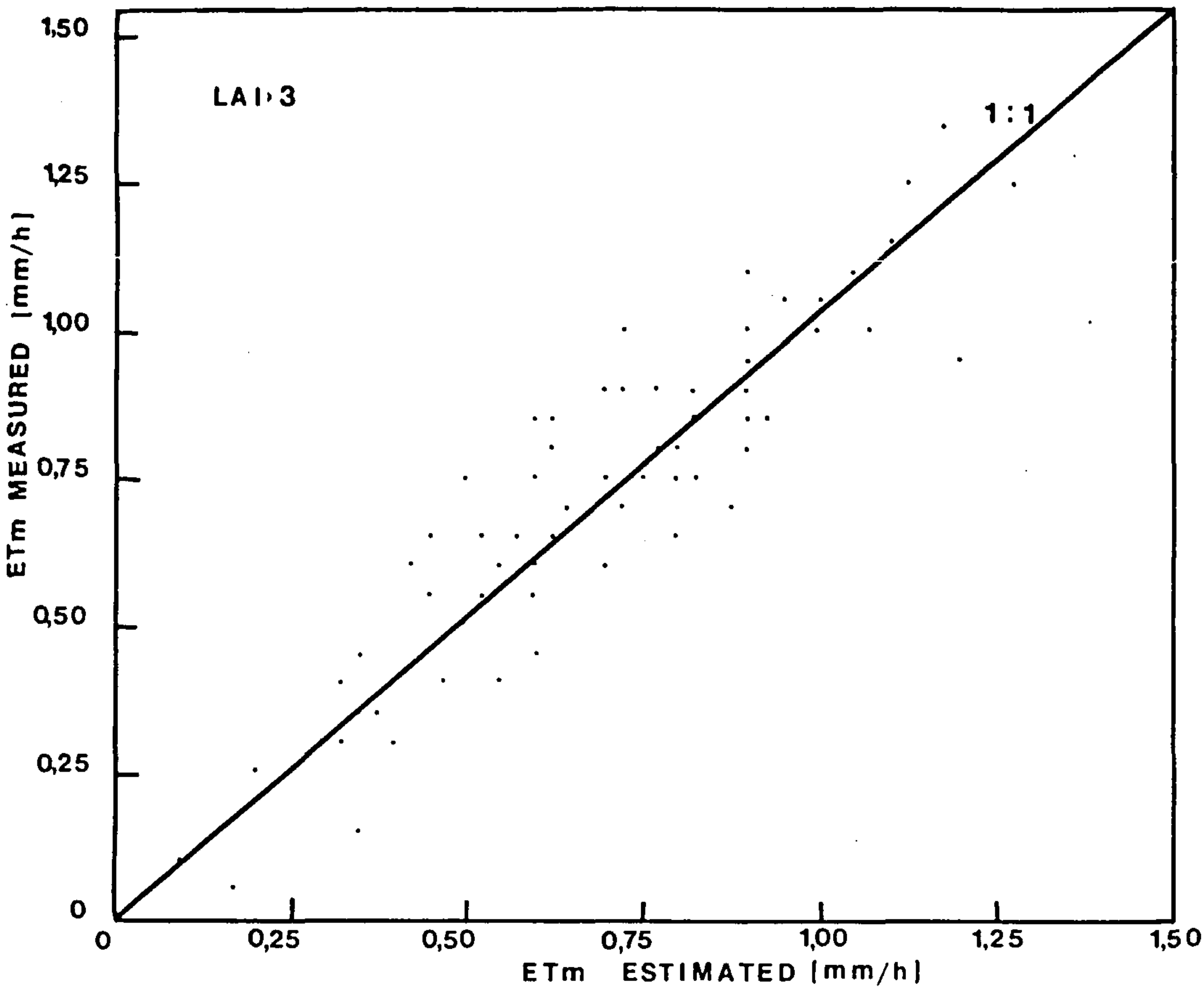


Fig. 5.1 - A comparison between Em measured and estimated using the Penman-Monteith equation assuming neutral atmospheric conditions (i.e. Φm = 1).

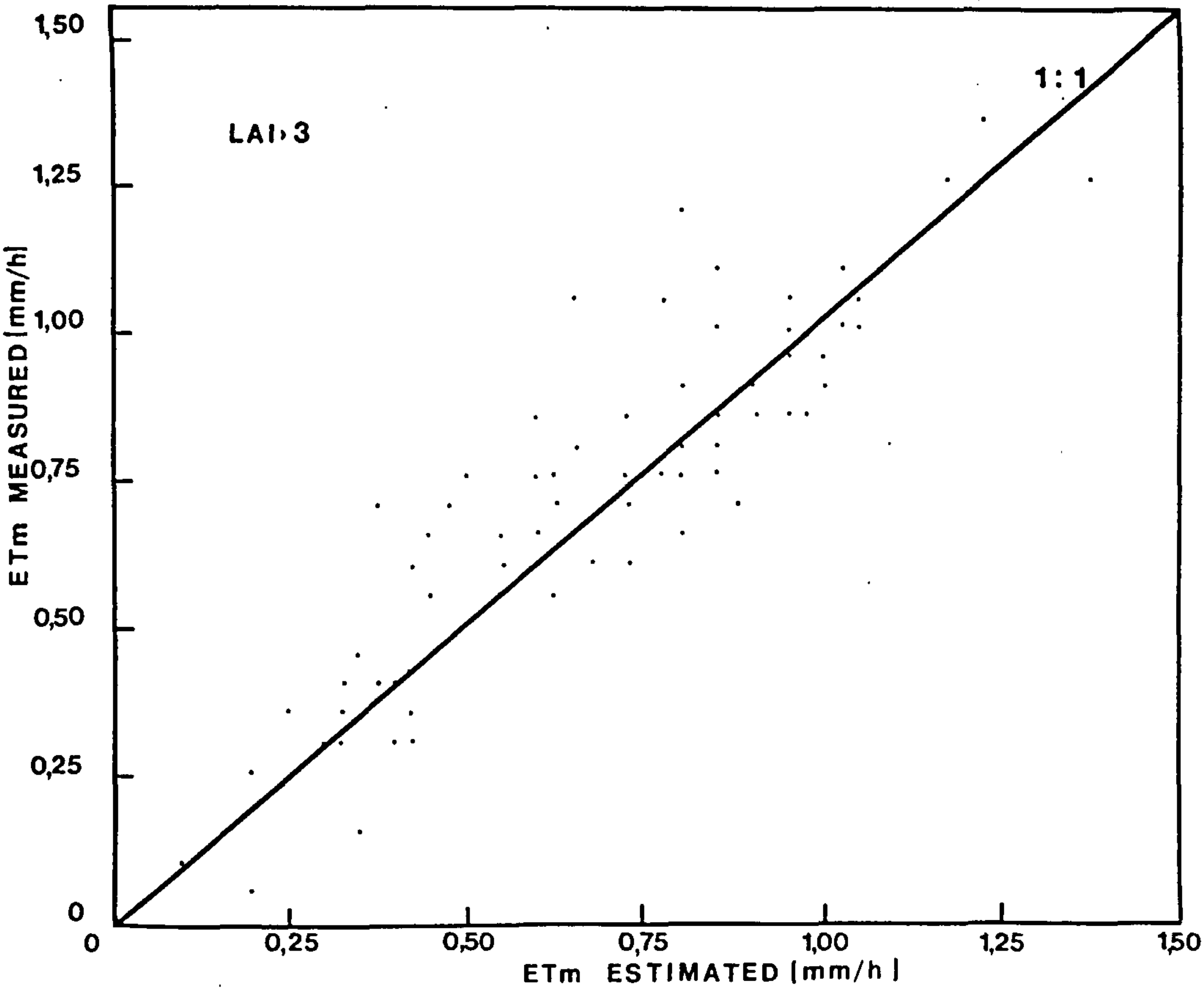


Fig. 5.2 - A comparison between Em measured and estimated using the Penman-Monteith equation corrected for atmospheric stability as measured over grass (i.e. $\Phi m = f(Ri)$).

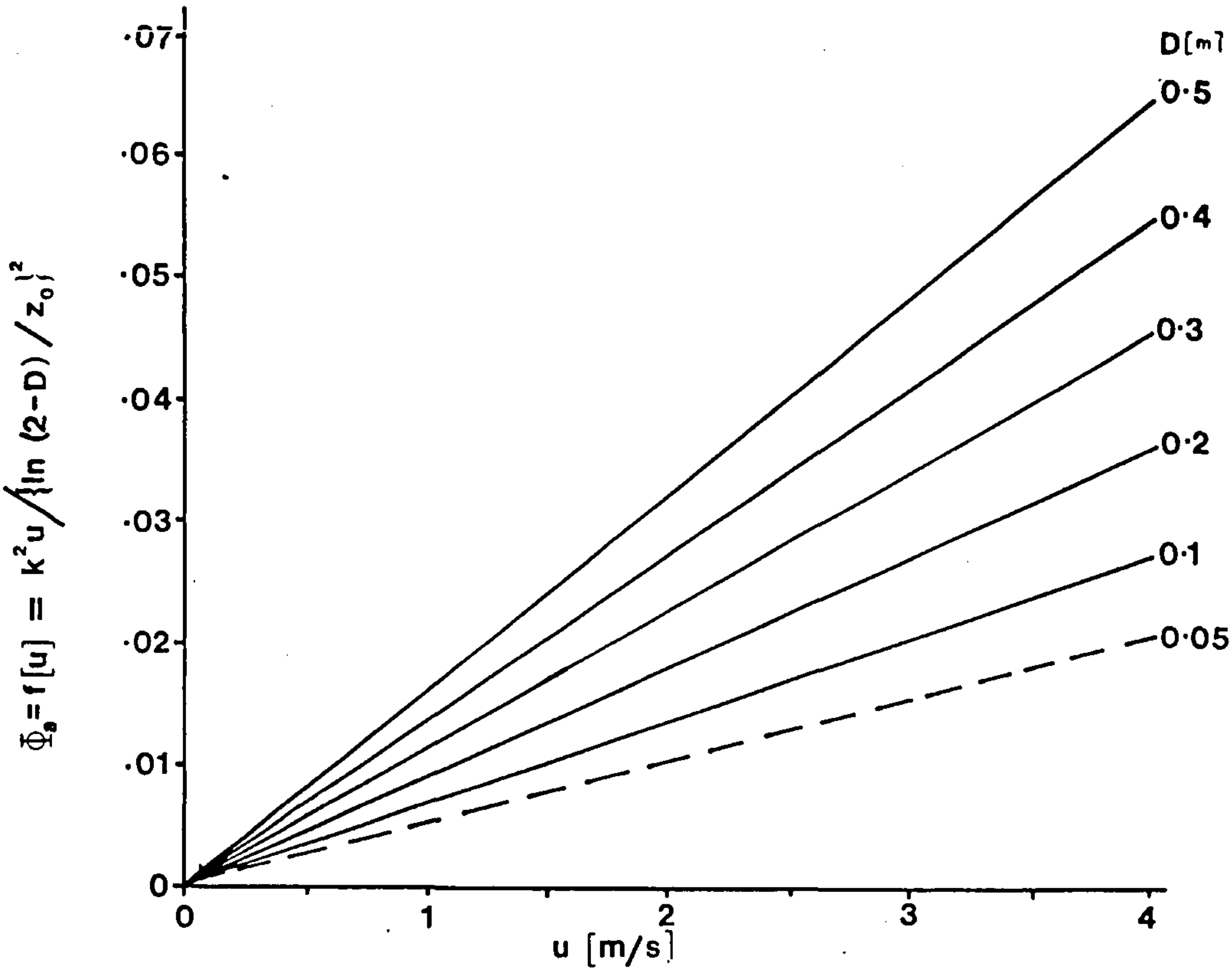


Fig. 5.3 - Variation in aerodynamic conductance with zero plane displacement.

TABLE 5.1 - Frequency distribution of the stability function, Φ_m.

Class interval	Frequency (n)	Percentage frequency (n/N x 100) : N = 63
$1,20 < \Phi_m < 1,80$	5	8
$1,10 < \Phi_m < 1,20$	2	3
$1,00 < \Phi_m < 1,10$	3	5
$0,90 < \Phi_m < 1,00$	28	44
$0,80 < \Phi_m < 0,90$	17	27
$0,60 < \Phi_m < 0,80$	8	13

TABLE 5.2 - Summary of the statistical tests carried out between hourly values of Em measured and Em estimated with ($\Phi_m = f(Ri)$) and without ($\Phi_m = 1$) adjustment for the existing atmospheric stability.

Appropriate coefficient	Comparison with $\Phi_m = 1$	Comparison with $\Phi_m = f(Ri)$
Correlation coefficient (r)	0,91	0,89
Slope (m)	0,97	0,88
Intercept (b)	0,05 mm/h	0,11 mm/h
Simulation index	0,97	0,94
Systematic error	0,03 mm/h	0,04 mm/h
Unsystematic error	0,12 mm/h	0,13 mm/h
Mean residual	0,09 mm/h	0,10 mm/h
Mean difference	0,03 mm/h	0,03 mm/h
Mean absolute difference	0,09 mm/h	0,10 mm/h

TABLE 5.3 - Statistical analysis of agreement between daily values of total evaporation (mm/d) as measured by the lysimeter, Elys, and calculated from micrometeorological data using the Penman-Monteith equation, Em, assuming atmospheric neutrality (Φm = 1) or adjusting for atmospheric stability (Φm = f(Ri)).

	Elys (mm/d)	
Y	Elys (mm/d)	
X	Em (mm/d)	
	Φm=1	Φm=f(Ri)
n	9	9
SLOPE	0,82	0,88
INTERCEPT (mm/d)	0,99	0,72
r	0,90	0,88
MEAN OF MEASURED VALUES	6,07	5,89
MAD (mm/d)	0,65	0,52
SIMULATION INDEX	0,94	0,93

TABLE 5.4 - Statistical analysis of relationship between hourly net radiation minus soil heat flux and hourly incoming solar radiant flux density, St.

Y	Qn-G (W/m^2)
X	St (W/m^2)
n	96
SLOPE	0,75
INTERCEPT	-72 W/m^2
r	0,96

TABLE 5.5 - Statistical analysis of the accuracy of different methods of measuring total evaporation, Em

Y	Bowen		Elys		Elys		Elys	Elys
X	Iter		Iter		Bowen		*Itera	**It86
	mm/h	mm/d	mm/h	mm/d	mm/h	mm/d	mm/h	mm/h
n	60	9	79	9	75	9	75	61
SLOPE	0,80	0,73	0,64	0,81	0,74	0,86	0,54	0,49
INTERCEPT	0,18	2,32	0,41	2,67	0,28	1,73	0,39	0,29
CORRELATION COEFFICIENT	0,78	0,73	0,58	0,73	0,75	0,68	0,50	0,68
MAD	0,16	1,33	0,28	2,00	0,19	1,05	0,25	0,18
SIMULATION INDEX	0,85	0,66	0,66	0,56	0,83	0,74	0,80	0,80
SYSTEMATIC ERROR							0,16	
UNSYSTEMATIC ERROR							0,17	
MEAN RESIDUAL							0,14	
MEAN DIFFERENCE	0,09	1,33					0,00	
MAX ABSOLUTE DIFFERENCE							0,52	
MEAN Y	0,43	3,60	0,72	5,60	0,71	6,00	0,71	0,55
MEAN X							0,55	

*Itera are values obtained in 1985 with the iteration technique assuming that the relative humidity at the momentum exchange level was 10% higher than that at the 2m height.

**It86 are values obtained in 1986 using the original unaltered iteration technique.

TABLE 5.6 - Statistical analysis of relationship between temperature and relative humidity at the momentum exchange level in the wheat crop (o) and the corresponding elements at a reference height of 2m (r).

X Y	Tempo Temp	Rho Rhr
	(°C)	(%)
n	115	115
SLOPE	0,97	0,91
INTERCEPT	0,63	9,25
r	0,99	0,95
MEAN OF MEASURED VALUES	21,31	46,82
MAD	0,36	5,99
SIMULATION INDEX	0,99	0,95

TABLE 5.7 - Statistical analysis of agreement between crop surface temperature calculated using the iteration technique (TO-iter) and measured by thermometer at the momentum exchange level (TOMES) and the infrared thermometer (IRT).

Y	TO-iter	
X	TOMES	IRT
	(°C)	(°C)
n	66	25
SLOPE	1,15	1,03
INTERCEPT (°C)	-1,90	-0,31
r	0,92	0,95
MEAN OF MEASURED VALUES(°C)	26,33	29,65
MAD (°C)	2,43	1,90
SIMULATION INDEX	0,92	0,95

CHAPTER 6

DESCRIPTION OF THE STRESS EVENTS DURING 1985

In order to develop and validate the PUTU models, it was necessary to identify stress periods in the wheat growing seasons. The procedures adopted in obtaining the results discussed here are reported in Chapter 7. The objective of this chapter will be to describe the stress events used to validate the capability of PUTU 9.86 to determine the onset of crop water stress.

RESULTS

Leaf water potential will be considered to be a positive entity. The scenario describing two stress events in 1985 are depicted in Fig. 6.1. It is evident that during stress, leaf water potential rises to almost 3,0 MPa. From Fig. 6.2 it may be seen that the difference in leaf water potential and foliage temperature between the stress and control plots provides an excellent indication of crop water stress.

De Jager, Bristow and Van Zyl (1984) provide evidence that leaf water potential in the wheat crop maintains a constant level during the middle part of each day. This is clearly illustrated in Fig. 6.3 under conditions with no water stress. This phenomenon was repeatedly observed on many occasions during the experiments.

In 1985, Plot 3 (as described in Chapter 7) was stressed around DOY 320. The response of leaf water potential during the development of water stress is depicted in the four graphs of Fig. 6.4. It is evident that in the stressed plot (Plot 3), leaf water potential gradually increased to a level exceeding 2,5 MPa. The plateau during day-light hours was still evident.

Crop foliage temperatures also provide useful indicators of stress. Once again the progressive development of stress in Plot 3 around DOY 320 may be followed by comparing (experimental Plot-wet plot) foliage temperatures, as measured by infrared thermometer, on stress and control plots (Fig. 6.2 and 6.5 through 6.7). The effect of cloud in the 14th hour of DAY 320 is also evident from Fig. 6.6.

All these figures (6.1 through 6.7) clearly indicate that stress occurred around DAY 285 in Plot 2 and around DOY 320 in Plot 3.

CONCLUSIONS

Bearing in mind the convention of positive leaf water potentials, it may be concluded that, in 1985, stress events took place in Plot 2 and Plot 3. In Plot 2 leaf water potentials indicate that stress commenced on DOY 280 (leaf water potential 1500 kPa) and gradually deepened to where leaf water potential reached approximately 2700 kPa on DOY 284 and then remained above 2400 kPa until DOY 286 when irrigation took place. A similar development was recorded around DOY 320. Leaf water potential started rising gradually from 2200 kPa on DOY 318 to around 3000 kPa on DOY 322.

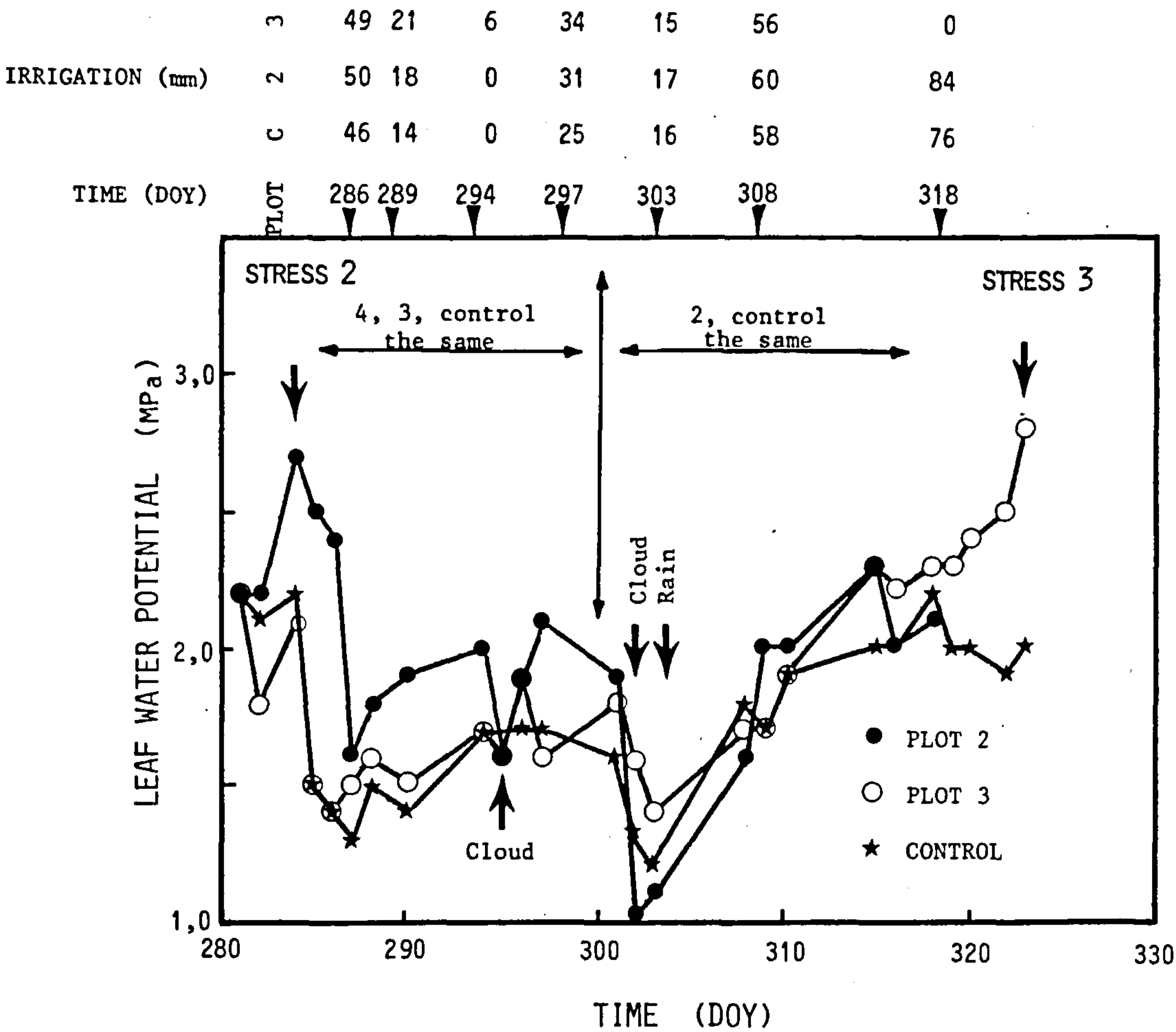


Fig. 6.1 - Scenario of noon mean crop leaf water potential on stress plots and the control plot at West Campus in 1985. Irrigation dates and amounts are indicated.

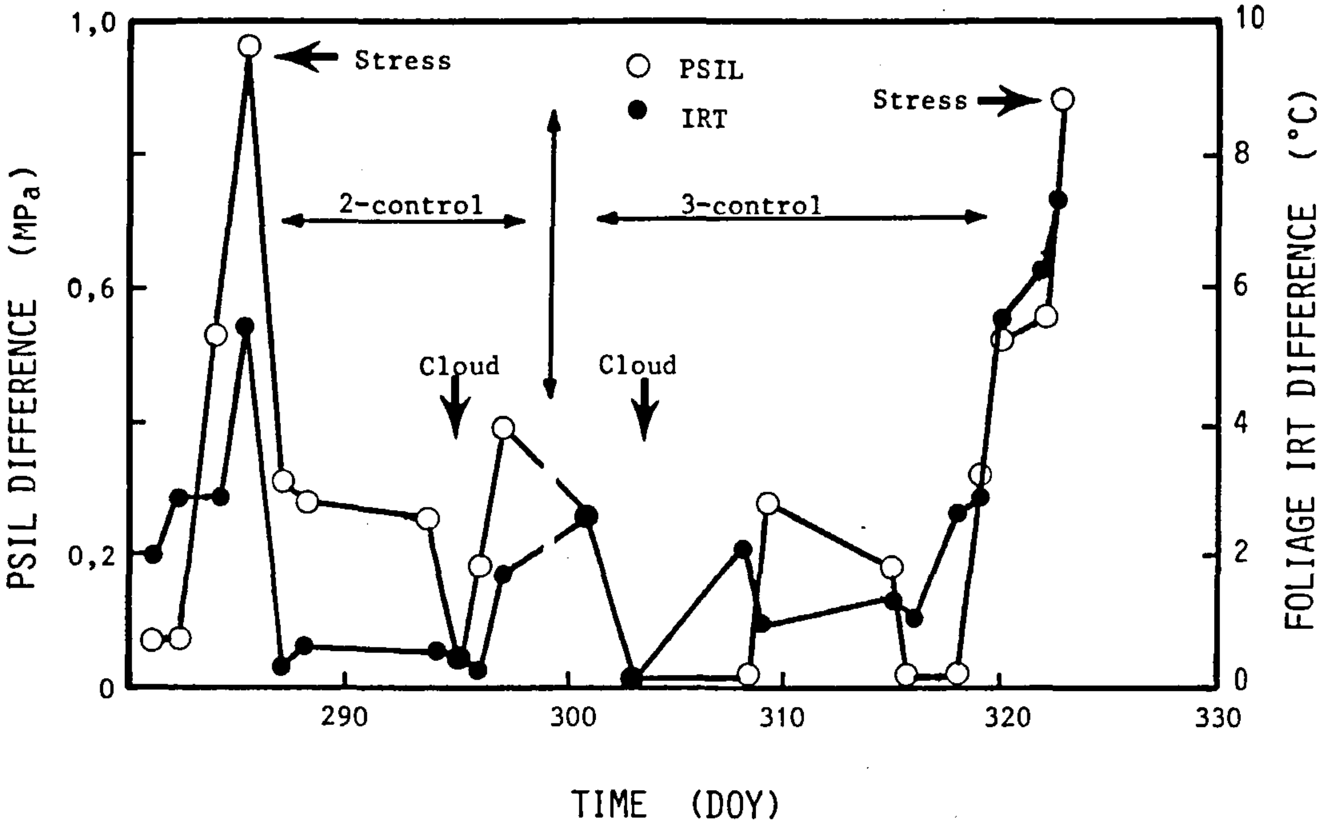


Fig. 6.2 - Scenario of difference in leaf water potential, PSIL, and foliage temperature, IRT, between stress and control plots on West Campus 1985.

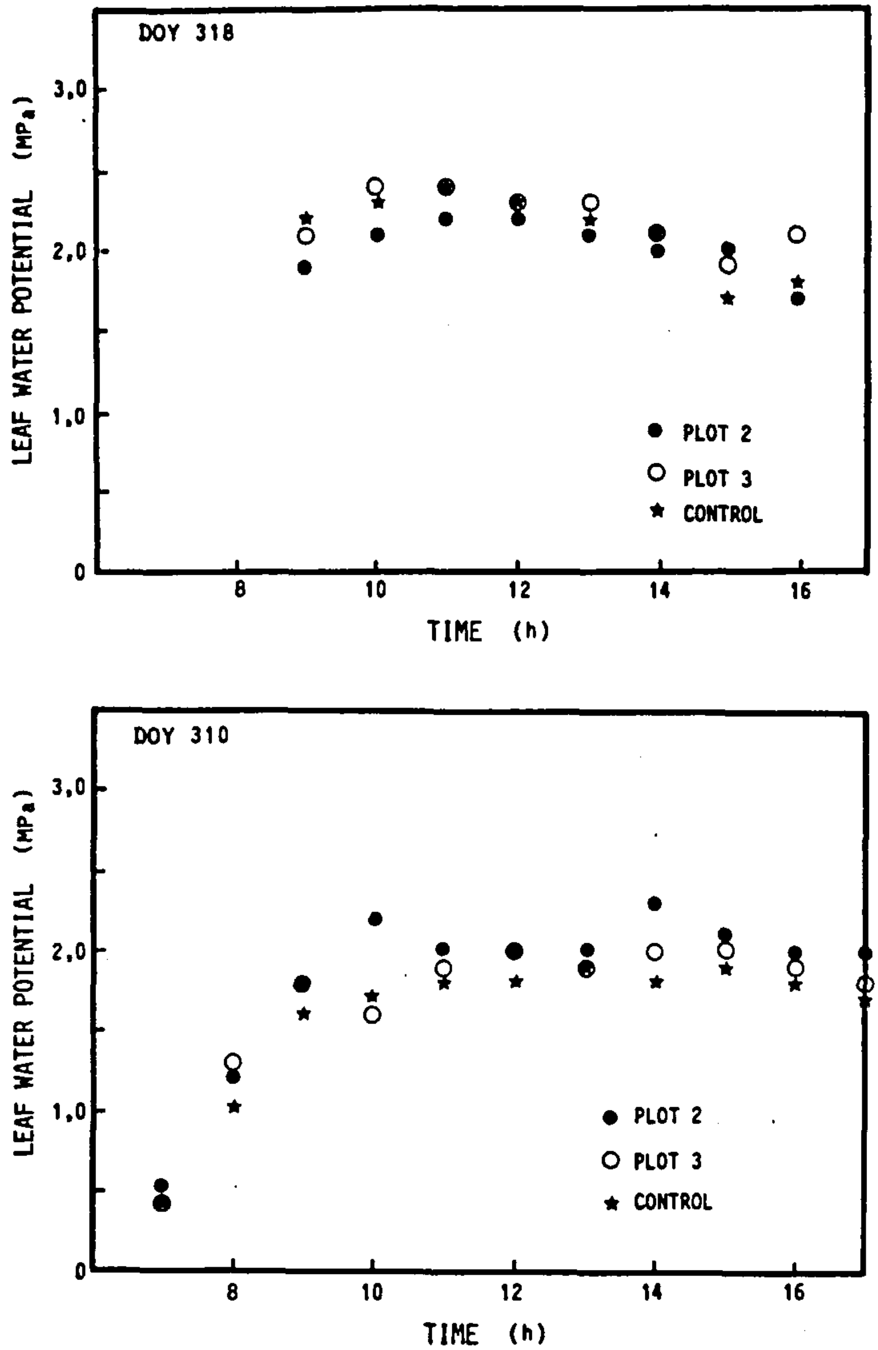


Fig. 6.3 - Hourly crop mean leaf water potential in Plot 2, Plot 3 and the Control Plot on DOY 310 and DOY 318 before the onset of water stress, West Campus 1985.

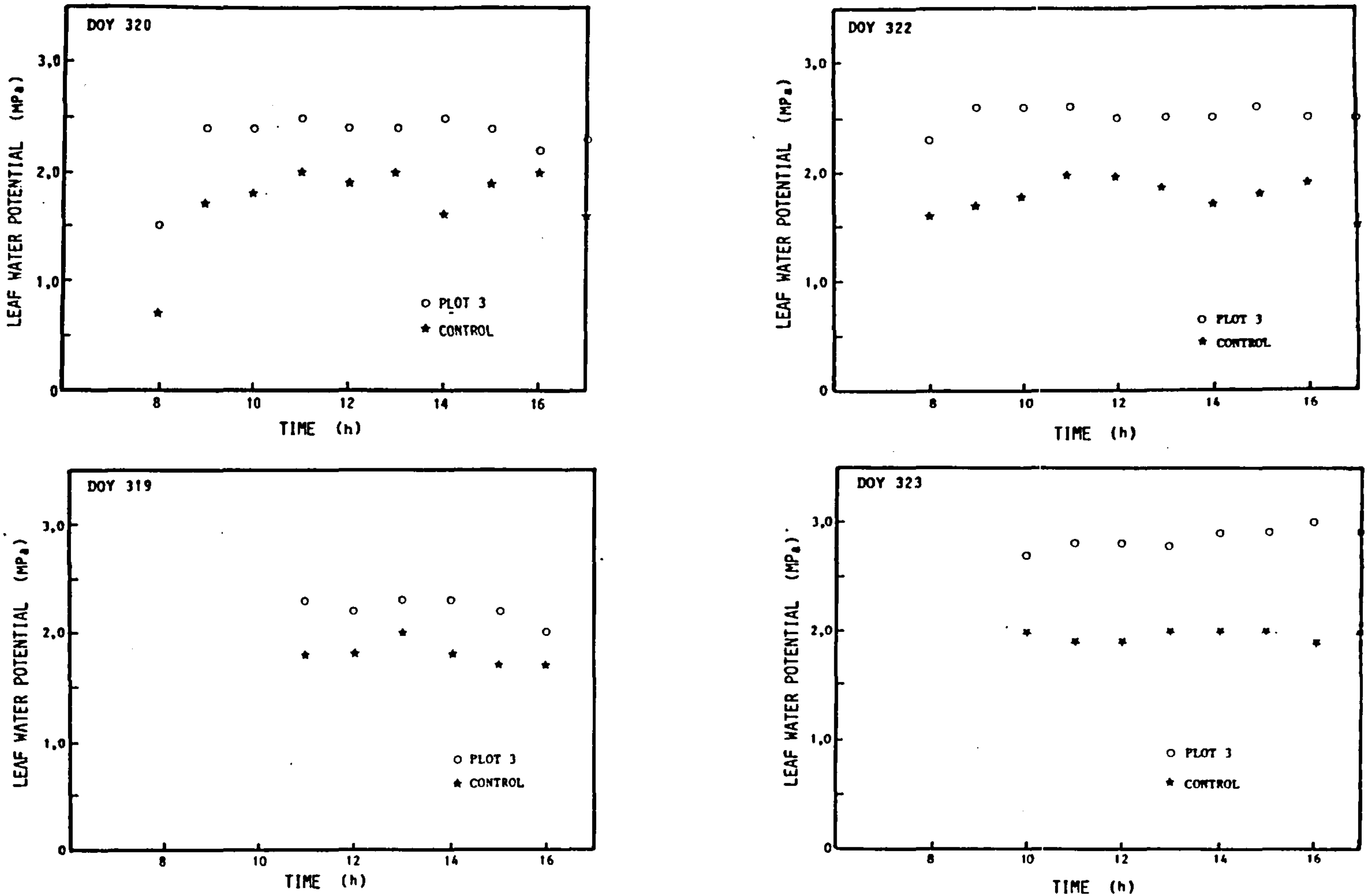


FIG. 6.4 - HOURLY CROP MEAN LEAF WATER POTENTIAL ON PLOT 3 AND THE CONTROL PLOT ON DOY 319 THROUGH DAY 323 ILLUSTRATING THE EFFECT OF WORSENING WATER STRESS UPON LEAF WATER POTENTIAL ON WEST CAMPUS IN 1985.

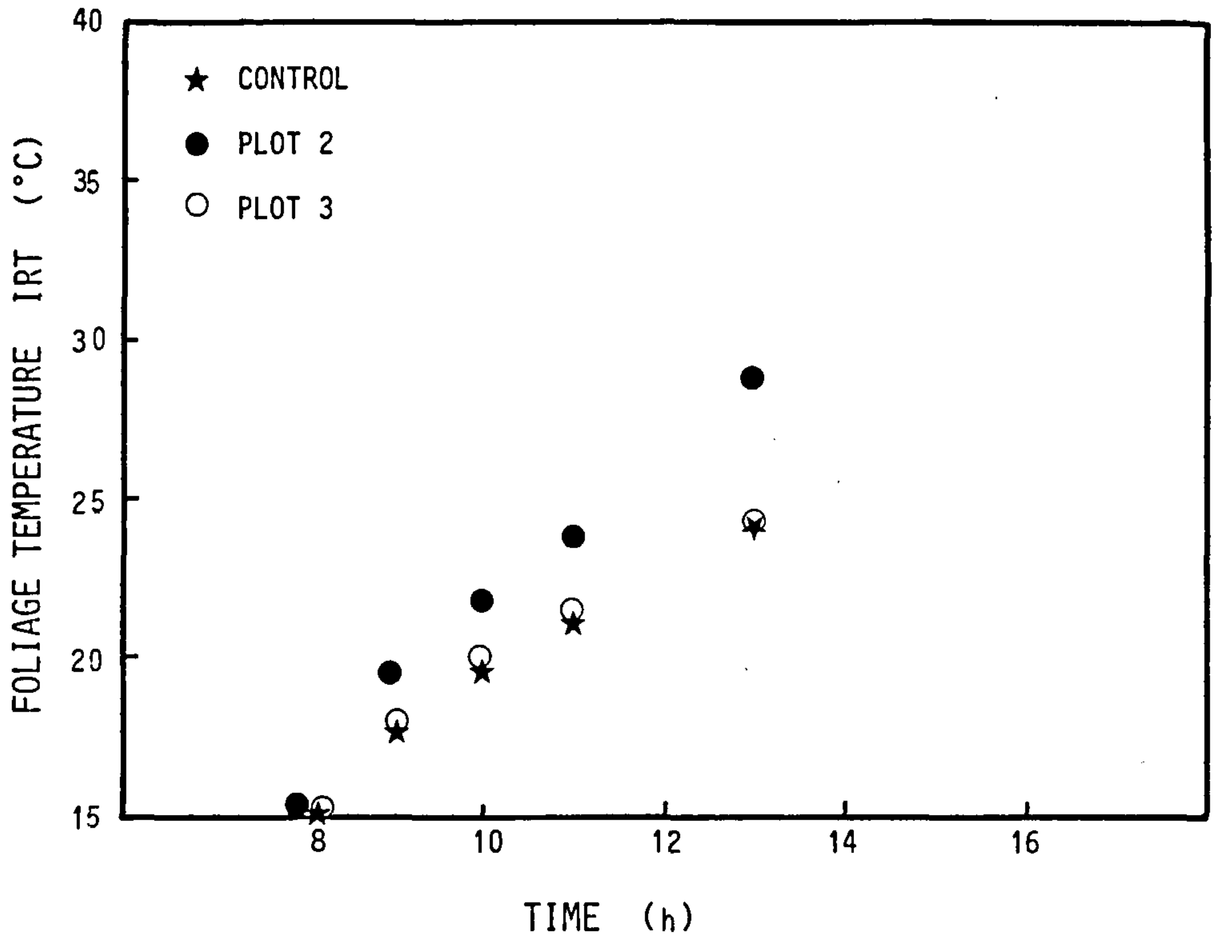


Fig. 6.5 - Comparison of Plot 2, Plot 3 and Control plot foliage temperatures on DOY 285 at West Campus in 1985.

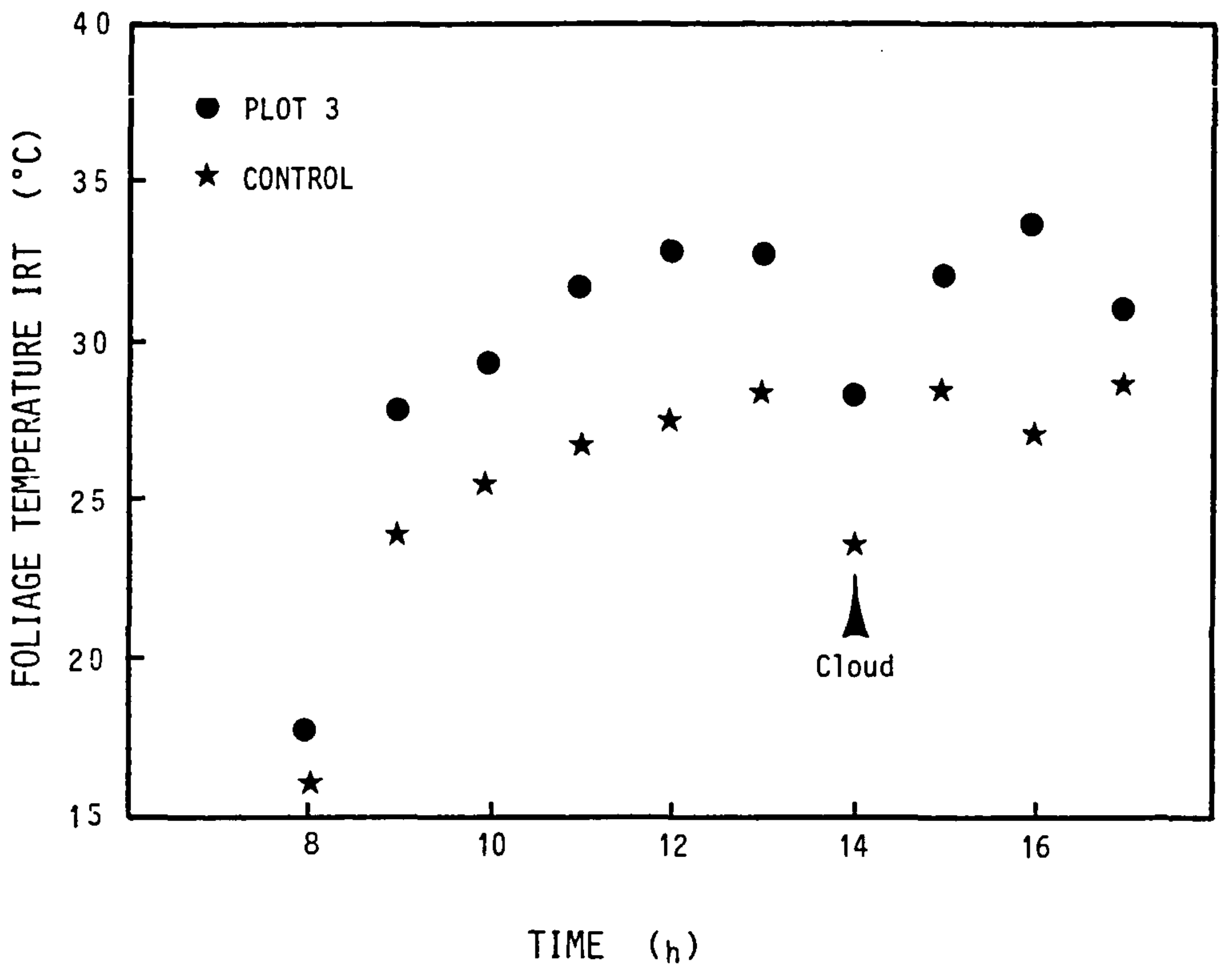


Fig. 6.6 - Comparison of hourly wheat foliage temperatures in the Control plot and Plot 3 on DOY 320 at West Campus 1985.

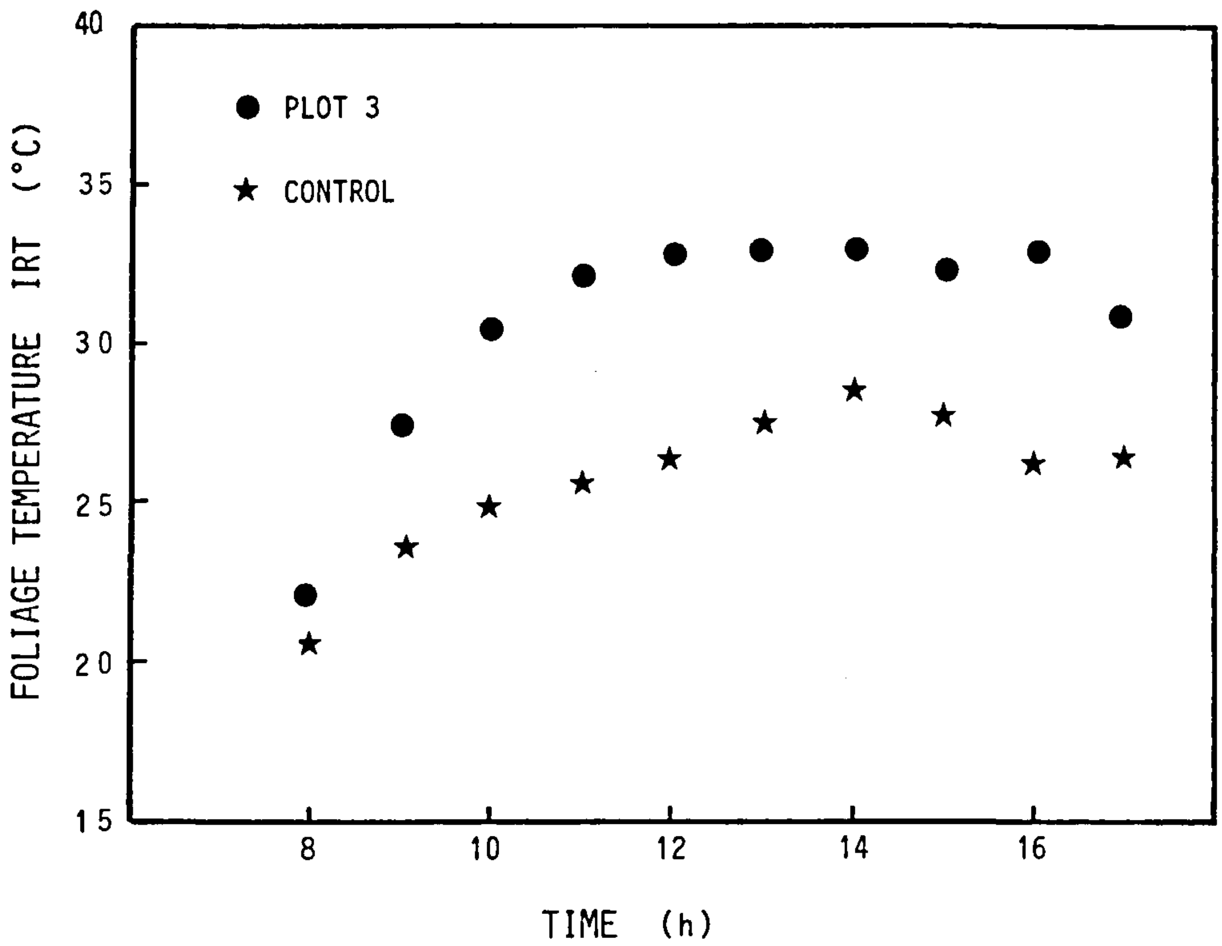


Fig. 6.7 - Comparison of Plot 3 and Control plot foliage temperatures on DOY 322 at West Campus in 1985.

CHAPTER 7

PUTU 9.86 VALIDATION

OBJECTIVE

The objectives of this phase of the project were a) to establish suitable facilities for accurately measuring wheat crop water use, and b) to test and improve the computer routines for simulating water use and the onset of crop water stress in the PUTU 9.86 irrigation scheduling model.

PROCEDURE

The lysimeter

The lysimeter was installed in the middle of the experimental area on West Campus. Its dimensions are 3,16 x 3,1 x 2,1 m, i.e. 10 m x 2 m deep. This bin was installed above a mechanical system provided by Klerkscale*, Potchefstroom. It was provided with six steel sheets arranged 100 mm above the bottom of the tank in such a way as to permit water to seep between the plates for collection and removal. Upon this base 12 mm of granite chips were evenly spread to a depth of 200 mm. This porous layer was covered with 4,4 mm thick (grade U64) non-woven continuous filament needle punched Polyester Geofabric (Bidim*). During September, 1983, the bin was filled with soil. Its total mass approximated 50 t. The soil in the lysimeter may be classified

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*Bidim - manufactured by Kaymac in S.A. and supplied by Noel Hunt Geofabrics (Pty) Ltd, P O Box 34179, Jeppestown 2043. Any reference thereto and to Klerkscale does not represent an endorsement by the UOFS.

as Hutton form and Middelburg series. It was collected from the orthic A and red apedal B horizons of a neighbouring Bainsvlei soil.

The accuracy of the Penman-Monteith equation has been proven in Chapter 5. Reference evaporation, Er, was simulated using the form of the Penman-Monteith equation used in PUTU 9 for a constant crop height of 50 mm. Maximum total evaporation Em was estimated using crop height modelled as in APPENDIX III.

An underground water piping system was installed to supply the 5 ha experimental area surrounding the lysimeter with irrigation water (see Fig. 7.0).

In 1984, 3 ha of SST-4 wheat were established around the lysimeter. It was planted on 1984.07.02 in 300 mm wide rows and resulted in a plant density of 206 pl/m . Three experimental plots were utilized - the lysimeter, Plot 1 (120 x 5m) which received a stress treatment in the reproductive phase and Plot 2 (120 x 5m) which was stressed in the vegetative phase. The lysimeter was well watered up to 1984.10.26. The entire field received 772 kg/ha of 2:3:0 (21) fertilizer.

In 1985, 4 ha of SST-44 wheat were established around the lysimeter. It was planted in 100 mm wide rows at a seeding rate of 220 pl/m (90 kg/ha) on 1985.07.01.

In 1985 six experimental plots were used. Five plots, numbered 1, 2, C, 3 and 4, were sited in a north-south line 80 m east of the lysimeter. They were irrigated by a set of line sprinklers, installed exclusively for this purpose. The soil in the sixth (wet) plot, sited 120 m south-east of the lysimeter, was held close to maximum soil water content throughout the season. All plots were approximately 10 x 10 m in size. Each experimental plot had three neutron probe access tubes imbedded in a triangle of side 0,5 m. A raingauge was placed one metre south of the access tubes. Each plot centre was 2,25 m west of a sprinkler riser.

The soil of the experimental terrain is of Sterkspruit form, Sterkspruit series. Fig. 7.0 illustrates the soil profile in the pit prepared for the lysimeter. A calcerous layer is present at 750 mm. No soil water extraction was measured at this depth in the plots.

Tensiometers, for monitoring soil water potential, were installed in the lysimeter (1984 and 1985) and Plots A and B in 1984. The porous cups were placed at depths of 150 mm, 300 mm, 600 mm and 900 mm.

In 1985 neutron probe access tubes were installed in the lysimeter (4 tubes) and experimental Plots 1, 2, C, 3 and 4 (3 tubes each). Measurements were taken at 150 mm intervals down to 1200 mm in the lysimeter and to 800 mm in the plots.

The irrigation treatments for 1985 applied are illustrated in Fig 6.1. Essentially C, the control plot, was given adequate water to prevent water stress. In Plot 1 and 2 early stress (± DOY 284) was permitted. While stress was allowed late in Plot 3 and 4 (± DOY 319). Irrigation and rainfall events are recorded in Table 7.5.

Soil water potential, crop height, leaf area and foliage temperatures were measured at regular intervals. Total evaporation was measured in the lysimeter.

Infra-red thermometer readings were made in all three sites using the Teletemp AG24 unit. It was initially calibrated on setting 0,89 and 0,91 following the method of Berliner, Oosterhuis and Green (1984). Calibration yielded an r of 1,0; a systematic error of 0,3 °C and an unsystematic error of 0,1 °C on the 0,89 setting which was subsequently used in the field measurements. The standard error of estimate of the regression was 0,12 °C.

RESULTS

It must be emphasized that all results quoted for 1984 were obtained during model development. The data for 1985 were strictly reserved for verification of model reliability. Standard statistical tests were applied. The symbols used to denote the different test parameters are described in Table 7.1.

Evaporation through the soil surface, Es

The PUTU 9 model used a soil surface drying function which was an exclusive function of time, viz.

$$Fg = EXP(-0,4\ t) \qquad ...(7.1)$$

where,

Fg is the proportion of maximum evaporation permitted by surface soil water status, and

t is the number of days since the last irrigation or rainfall event.

Thus Fg = Es / Er, if it is assumed that evaporation from wet bare soil equates to evaporation from a short grass surface, Er.

The problem with this equation is that the surface loses water at a rate independent of the soil water content in the top layer. It is however logical to expect such water loss to be related rather to soil water content in the top layer than to time. Instead of Eqn 7.1, it was assumed that water evaporated through the soil surface stems solely from the top 100 mm of soil and that the drying rate in the top soil layer bears an exponential relationship to water content in this layer.

Essentially, this means that Fg is a function of the total amount of water evaporated since the last wetting event. The latter is equal to the depletion below maximum soil water content in the top layer. Consequently, the proposed model has the defining equation

$$\delta Fg / \delta VDEF1 = -a \cdot Fg, \qquad ..(7.2)$$

which may be solved given the boundary condition Fg = 1 when VDEF1 = 0. Thus,

$$Fg = EXP(-a \cdot VDEF1) \qquad ..(7.3)$$

where VDEF1 in mm/m is the soil water deficit (decrement below field capacity) in the top soil layer and <a> is a constant. The value of a = 0,03 m/mm was obtained by assuming that Fg decreased to approximately 0,1 when the soil water content of the top layer is depleted by 77 mm/m (approximately 75 % of plant available water).

The model represented by Eqn 7.3 was tested against data measured in the lysimeter following two wetting events in 1984. The accuracy of the model is reflected in Fig. 7.1. Statistical tests yielded an SI = 0,99 and MAD = 0,03. It was concluded that Eqn 7.3 was an accurate model for describing water loss through the soil surface.

Modelling

The data collected were used to determine the onset of stress periods in the various plots (see Chapter 6) and to test the PUTU 9 model which is also described in Chapter 2. The 1984 data were used further to fine tune the PUTU 9.86 model. In particular, the leaf water potential and soil water potential observations were needed to evaluate KSPo, the maximum soil-root conductance, by trial and error. The best value found was KSPo = $-1,2 \times 10^{-3}$ mm/(d kPa m pl).

Relative vegetative evaporation, Fh

The scenario of simulated relative vegetative evaporation, Fh, is given in Fig. 7.2, 7.4, 7.5 and 7.6. The ease with which the onset and duration of water stress may be identified from a scenario of Fh is evident from these. The good agreement between the scenario in Plot 1 and Plot 2 in 1985 (Fig. 7.5) indicates that the model is consistent.

The timing of stress in 1984 (see Chapter 6) is shown in Fig. 7.4. This was compared with stress incidence recorded by IRT and Scholander bomb. Firstly, in Plot 1 and 2, on DOY 285 (1984), infra-red temperatures were 3,7 ^{o}C higher than in the lysimeter. Furthermore, leaf water potential was 2100kPa on DOY 286. The model therefore probably did not predict a partial stress which might have been present. Thereafter, IRT records indicated stress in Plot 1 on DOY 296 and 297 as did a leaf water potential of 3400 kPa on DOY 303 and DOY 304. In Plot 2, the IRT record showed stress from DOY 281 to 285 and also on DOY 292, then again from DOY 296 to 298 as well as on DOY 303 and 304. Leaf water potential measurements reinforced this with values on DOY 286 and

303 in excess of 2700 kPa. The scenario of Fh in Fig 7.4 accurately reflects all these as days on which crop water stress occurred.

In 1985 more critical tests on model ability to simulate onset of stress were undertaken. In Chapter 6, two stress events in 1985 were described. One commenced in Plot 2 on DOY 281 and the other on DOY 320 in Plot 3. The reliability of the model was assessed by comparing Fig. 7.5 and 7.6 with Fig. 6.1 through 6.7. The accuracy with which the onset of the stress periods described in Chapter 6 are identifiable in Fig. 7.5 and 7.6 attest to the reliability of PUTU 9.86 for scheduling irrigation. PUTU computed Fh = 89% on DOY 277 and Fh = 62% on DOY 278. It thus predicted the onset of stress two days early. On DOY 318 and DOY 319 simulated Fh equalled 80% and 14% respectively. These results indicate that the model simulated the onset of this particular stress period to within an accuracy of one or two days.

Relative total evaporation

The scenario of relative total evaporation for 1984 and 1985 is given in Fig. 7.3. The sharp fluctuations in the ratio of measured E/Em were due to the compounding influence of error in either lysimeter measurement or simulation. Reasonable agreement in trends in this ratio are apparent. Particularly noteworthy is the agreement in the gradual decrease in relative evaporation in the latter part of the grain filling stage in 1984 when stress occurred. The grain filling period ended on DOY 325. Examination of the simulated ratio at the end of the 1985 season indicates that the function describing the decrease in relative total evaporation with decreasing LAI at this time requires refinement. The model over-estimated measured values. This, however, took place late in the season and would affect neither yield nor scheduling.

Soil water content

Results of comparisons between measured and simulated soil water content are reported in Fig. 7.7 through 7.9 for soil layers deeper than 450 mm. In depths shallower than this, the rapid fluctuations in both measured and simulated soil water content make analysis difficult. The trends in soil water content in the various layers were simulated excellently (cf high r in Table 7.1). This indicates an accurate water extraction model. The absolute magnitude of soil water content in the different layers does not always correspond exactly to the measured values. This tended to cause a low simulation index of 0,73 for both the 450 mm and 600 mm layers. However, as will be seen, the water from the entire root profile can nonetheless be accurately simulated, notwithstanding poor simulation of water content in the individual layers. It is the total water use that is of importance where irrigation scheduling is concerned. The SI > 0,82 for the layers below 600 mm depths is highly acceptable. The agreement during dry-down down as stress commenced around DOY 320 seems good.

It may be concluded that the root distribution and soil water extraction model functioned satisfactorily.

Water use

Results obtained from modelling (1984) and validation (1985) of water use from the entire root zone are reported in Table 7.2. The excellent agreement between measurement and simulation are self evident. The results of the statistical tests applied on the results in Table 7.2 are given in Table 7.3. The high SI in Table 7.3 indicates a most reliable model.

General

It is difficult to decide between 5 kPa or 10 kPa which is the best limit for soil water potential at which maximum soil water content occurs. There is support in the literature for adopting either (see Mottram, 1985). The effect of using each was tested. Simulation runs were undertaken with both (see version I and II as described in Table 7.2). It is evident from Table 7.2, that selection of either would provide accurate simulation of water use. Maximum soil water content did not seem to affect simulated yields much (see tests in Table 7.4) when the Doorenbos and Kassam (1979) model was used.

Since soil water contents were simulated to within the range of uncertainty in Neutron probe measurements using the 10 kPa limit; it appears that this might be the better parameter.

Comparisons between measured and simulated yields are given in Table 7.4. While the number of values used here is too small to represent an exhaustive test of the model, it appears from these results that the Doorenbos and Kassam (1979) yield sub-model as used in PUTU 9.86 is in need of refinement. The SI of 0,76 with maximum water content taken at 5kPa, approaches acceptablity.

Study of the simulations showed that simulated leaf water potential maintained a low value (less than 1 MPa) in non-stress conditions and then rapidly approached 3 MPa at the onset of stress. The rate of change and non-stress values of this variable are lower than those measured. Hence, this sub-model also requires refinement. Although leaf water potential does not approach this stressed condition in the manner measured, it does indicate the time of onset of stress accurately. This is all that is required from an irrigation scheduling model. This plant water response may be rectified by modifying the function (after Botha, 1983) describing soil root hydraulic conductance, KSP. In order to improve the model, KSP must be made initially to decrease rapidly with decreasing soil water content and then less rapidly as the soil water content in the layer approaches wilting point.

CONCLUSION

Many more data would be required before conclusions beyond any doubt could be reached. Particularly the simulation of leaf water potential requires attention. However, from the evidence here presented it may be concluded that the PUTU 9.86 model accurately simulates the onset and duration of water stress. The total water use by the crop is also accurately simulated. As such it offers a reliable model for scheduling irrigation.

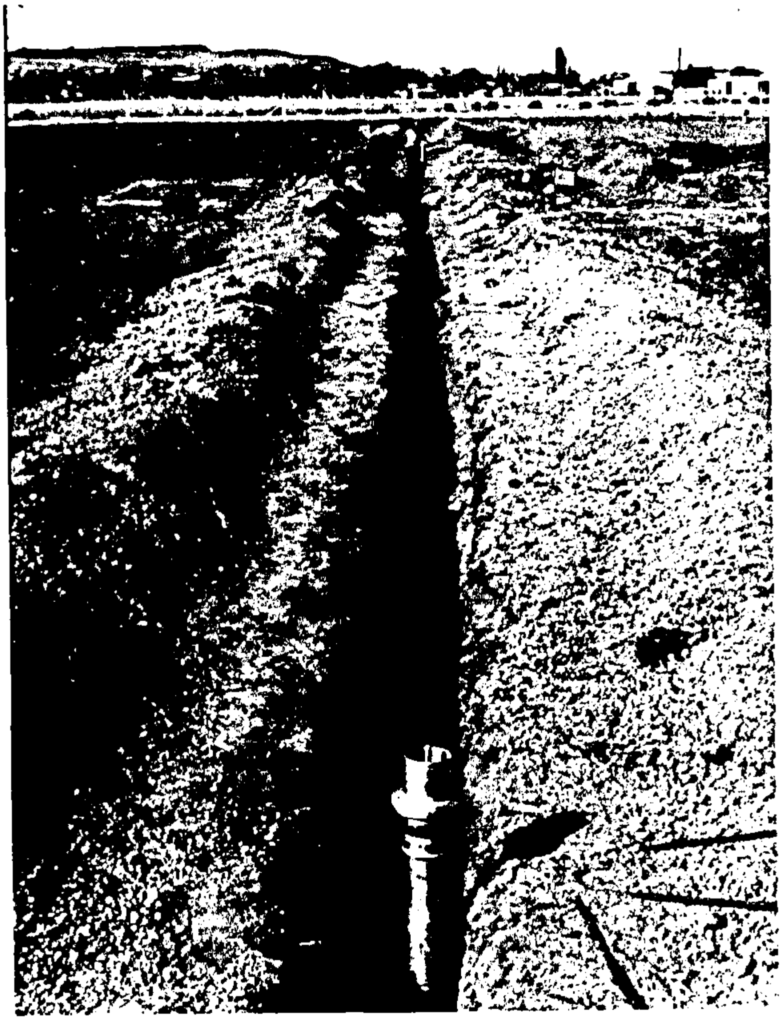


FIG. 7.0 - The soil profile in the pit in which the lysimeter was installed and the furrow excavated for the irrigation water supply pipe.

Table 7.1 - Statistical analysis of the accuracy of PUTU9-86 for simulating soil water content in five different soil layers during 1985.

	DEPTH (mm)				
	450	600	750	1050	1200
n	23	23	23	23	22
a	0,81	0,69	0,73	0,93	1,15
b (mm/m)	0,84	23,65	29,72	14,48	0,24
r	0,81	0,81	0,87	0,96	0,90
MEAN ($\overline{Y}$)	137,78	141,52	150,52	176,74	205,45
MAD (mm/m)	31,74	30,00	21,09	8,09	26,91
MAD/$\overline{Y}$	0,23	0,22	0,14	0,05	0,13
MD (mm/m)	-31,30	-27,64	-15,96	2,70	26,55
SI	0,73	0,73	0,86	0,98	0,82

n denotes the number of sets of values used in the comparisons,

a the slope of the regression curve,

b the intercept on the y-axis,

r the correlation coefficient,

Y the measured values,

$\overline{Y}$ the mean value of Y,

MAD the mean absolute difference between measured and simulated values,

MD the mean difference between measured and simulated values, and

SI the index of agreement (here named simulation index) of Willmott (1982).

TABLE 7.2 - Water use in the different growth stages and for the season as measured (lysimeter) and calculated by PUTU 9.86 in 1984 and 1985. Four different versions of the model as defined by I to IV below were tested.

YEAR	GROWTH STAGE	DURATION (days)	WATER USE IN (mm) MEASURED	CALCULATED I	II	III	V
1985	3	54	108	105	92		
	4	38	191	187	186		
	5	5	36	36	36		
	6	10	59	62	62		
	7	35	254	258	260		
	TOTAL		649	648	636		
1984	3	51	85	87	79	96	94
	4	43	199	228	228	256	202
	5	5	*	18	17	17	13
	6	10	78	65	66	64	49
	7	35	220	155	223	141	196
	TOTAL		618	553	613	574	554

Description of the significant modifications yielding the four (I-IV) different versions of PUTU 9.86 tested.

VERSION

I - Em = f(crop height)
Fle = 0,186*LAI
V01 at 10 kPa

II - Em = f(crop height)
Fle = 0,186*LAI
V01 at 5 kPa

III - Em = f(crop height)
Fle(Ritchie, 1972)
V01 at 10 kPa

IV - Em = Er
Fle(Ritchie, 1972)
V01 at 10 kPa

* Missing data

TABLE 7.3a - Statistical analysis of the accuracy of PUTU 9-86 for simulating total water use in the different growth stages. Five growth stages for 1985 and four growth stages for 1984 and the entire season totals were considered.

VERSION OF MODEL	1985			1984		
	Y	SI	MAD	Y	SI	MAD
			(mm)			(mm)
I	216	1,00	2,5	240	0,99	35
II	216	1,00	7,2	240	1,00	11
III				240	0,98	41
IV				240	0,99	26

$\bar{Y}$ - measured mean daily water use over all periods considered

TABLE 7.3b - Statistical analysis of the accuracy of the four versions of PUTU 9.86 for simulating mean daily water use in the different growth stages.

YEAR	VERSION OF MODEL	SI	MAD	Y	n
		(mm/d)	(mm/d)		
1984	I	0,92	0,94	5,01	4
	II	0,97	0,52	5,01	4
	III	0,87	1,27	5,01	4
	IV	0,83	0,95	5,01	4
1985	I	1,00	0,12	5,36	5
	II	1,00	0,18	5,36	5

Comparison of the SI and MAD for versions I and II with III and IV illustrate the improvement brought about by introduction of the relationship Fle = 0,186 * LAI.

TABLE 7.3c - Analysis of accuracy of version I of PUTU 9.86 for simulating seven-day totals of crop water use.

STATISTICAL PARAMETER	1984	1985
n	17	18
a	0,82	0,84
b (mm)	7,82	5,32
r	0,92	0,97
MEAN (Y)	35,68	33,42
MAD (mm)	4,59	3,87
MAD/Y (%)	12,86	11,58
MD (mm)	1,83	-0,02
SI	0,95	0,98

A seven day irrigation cycle was considered as this is the shortest probable. The mean difference of MD <,8mm means that over the entire season the error in computed water use will average less than 2,5%. The expected average error in a given irrigation period is <19%.

TABLE 7.4 - Percentage yield reduction as simulated by PUTU 9.86 for the various growth stages and the final simulated yield and measured final yield.

PLOT	MAX. WATER CONTENT AT	YIELD REDUCTION STAGE 3	4	5	6	7	FINAL YIELD CALCU-LATED	MEA-SURED	STD.DEV. MEASURED
	(kPa)	(%)	(%)	(%)	(%)	(%)	(kg/ha)	(kg/ha)	(kg/ha)
1985 L	5	5	0	0	1	1	6 510	5 240	
	10	5	0	0	1	1	6 510		
C	5	5	1	1	1	3	6 230	5 710	470
	10	5	1	0	11	7	5 320		
1	5	5	1	3	40	1	3 500	4 170	490
	10	5	1	17	40	1	2 520		
2	5	5	1	1	25	4	4 200	4 650	370
	10	5	1	7	40	4	3 010		
3	5	5	1	1	0	11	5 740	5 560	860
	10	5	1	1	10	18	4 550		
4	5	5	1	1	2	13	5 520	4 780	750
	10	5	1	2	17	18	3 990		
1984 L	5	6	0	1	1	10	5 740		
	10	6	1	0	1	24	4 760		
1	5	6	1	1	19	39	2 370		
	10	6	3	3	23	39	1 820		
2	5	6	3	1	6	40	3 100		
	10	6	6	0	6	41	2 870		
WET PLOT								5 380	940

Statistical tests on final yield

5 kPa   r = 0,87   SI = 0,80   MAD = 638 kg/ha   y = 5018 kg/ha

10 kPa   r = 0,78   SI = 0,64   MAD = 1125 kg/ha   y = 5018 kg/ha

* L denotes the lysimeter
  y denotes the mean measured yield

TABLE 7.5 - Water applications during the experiments of 1984 and 1985.

1984

DOY	PLOT L (mm)	PLOT 1 (mm)	PLOT 2 (mm)
165	2.6		
179	1.1		
180	0.9		
186	24.1	25.0	25.0
199	71.1	25.0	25.0
200	159.9		
214	4.86	25.0	25.0
216	1.49		
219	4.29		
222	1.13		
223	22.0	25.0	25.0
235	26.39	25.0	25.0
240	18.0		
244	1.1		
254	4.22		
257		25.0	
258			25.0
260	0.0		
262	22.23		25.0
263		25.0	
264	7.41		
265	0.97		
269	20.3		
270	9.98		25.0
271	2.58		0.0
275	20.94		25.0
276	0.0	25.0	
282		25.0	
284	12.0		
289	1.7		25.0
291		25.0	
292			
293	4.19		
296	11.66		
299		25.0	
300	0.0		
303	7.22		
304	2.33		
305	0.02		25.0
306	5.5		
313	15.70		
317	2.7		
320	3.8		
322			25.0

1985

DOY	PLOT L (mm)	PLOT 1 (mm)	PLOT 2 (mm)	PLOT C (mm)	PLOT 3 (mm)	PLOT 4 (mm)
198		50.0	50.0	50.0	50.0	50.0
200	2.9					
201	1.6					
206	58.0					
211	15.4					
214	8.9	50.0	50.0	50.0	50.0	50.0
221	13.8					
234	17.4					
245	8.5	50.0	50.0	50.0	50.0	50.0
249	14.1					
252	15.4					
258		90.0	90.0	90.0	90.0	90.0
260	17.9					
263		114.4	114.4	90.0	102.0	92.0
266	30.5					
269	26.9					
271		18.1	18.1	20.1	9.9	1.8
272	2.0					
274	24.1					
276	26.2	0.0	0.9	38.0	50.2	48.0
279						
282	34.5					
284	8.5					
285						
286	2.5	14.9	12.4	10.9	12.4	12.9
287	3.1	6.1	7.6	4.6	6.1	4.1
289		32.0	18.0	14.0	21.0	20.0
292	12.3					
294	3.2	0.0	0.0	0.0	5.7	7.0
297		78.8	31.4	25.0	33.6	31.9
299	8.4					
300	1.2					
302						
305		46.8	45.6	43.3	41.9	39.4
306	0.2					
315	7.8					
318	6.5	104.0	84.0	76.0	0.0	0.0

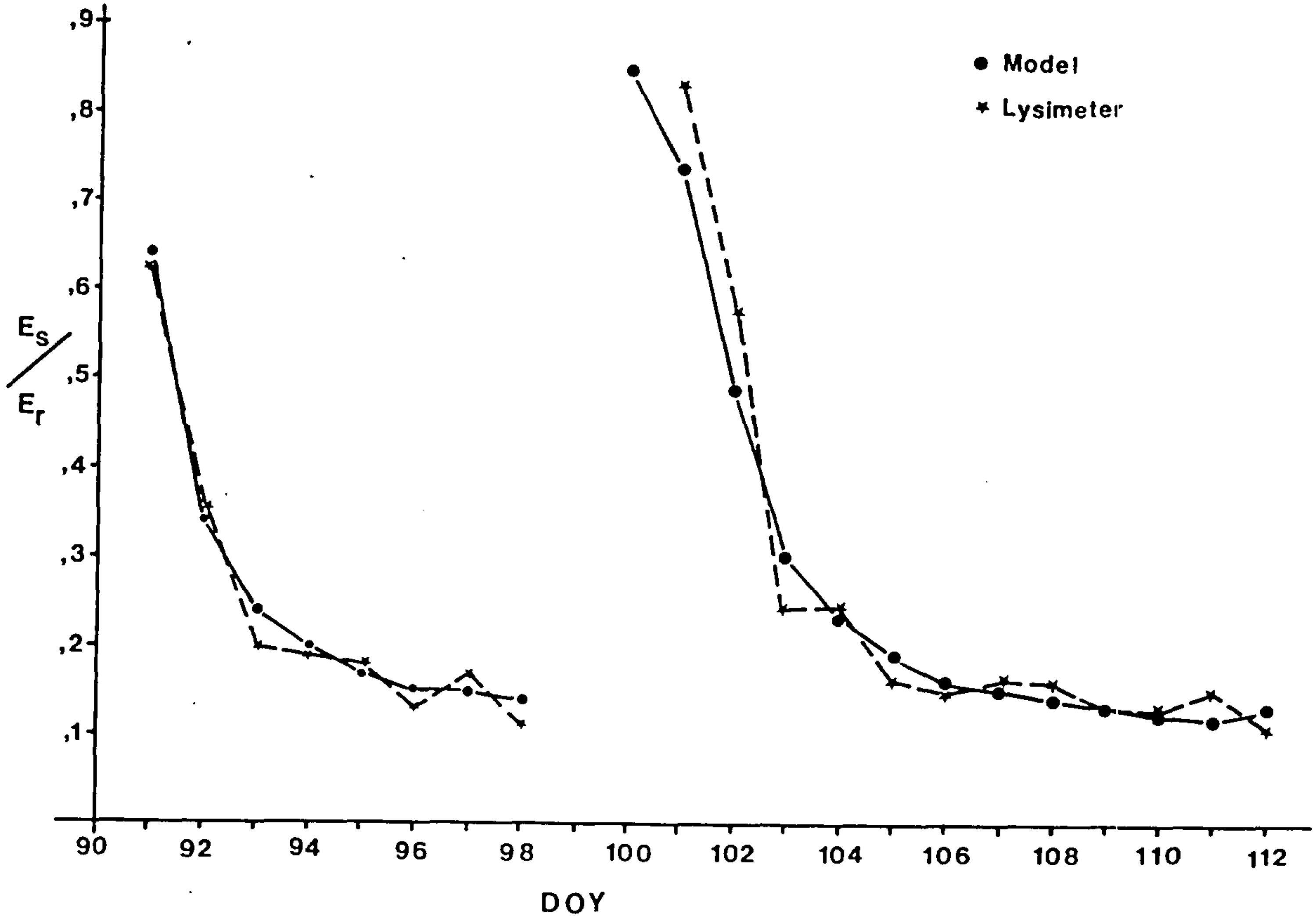


FIG. 7.1 - Simulated and measured values of the ratio of evaporation through the soil surface, Es, to reference evaporation, Er, following two wetting events during the 1984 season.

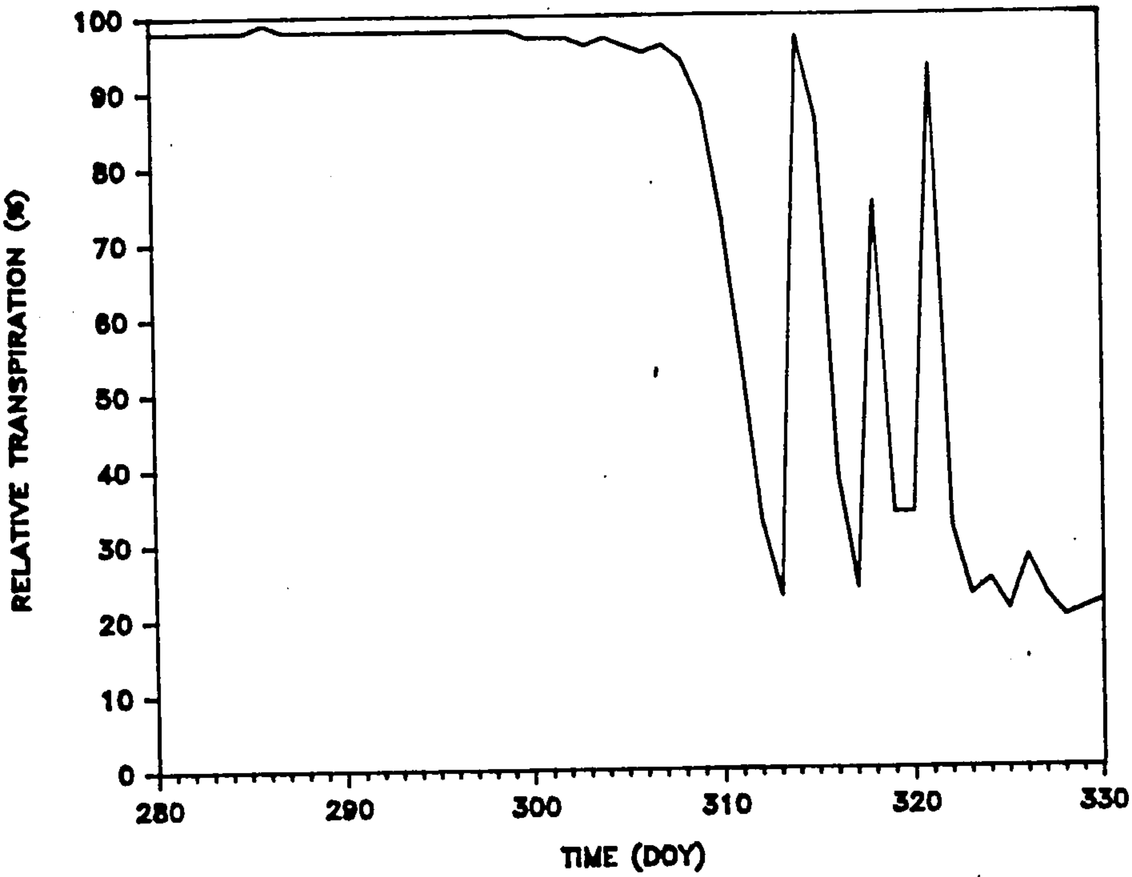


FIG 7.2a - Scenario of relative transpiration, Fh, as simulated by PUTU 9.86 for the lysimeter during 1984.

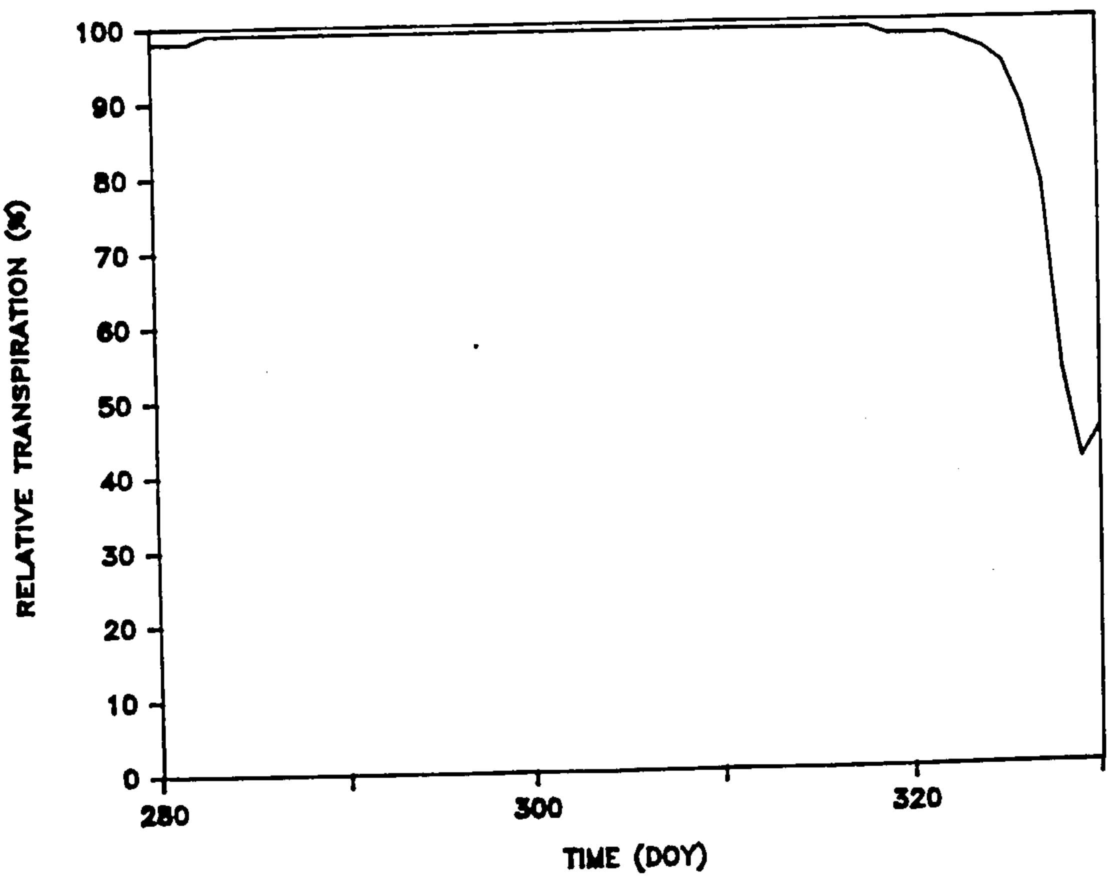


FIG 7.2b - Scenario of relative transpiration, Fh, as simulated by PUTU 9.86 for the lysimeter during 1985.

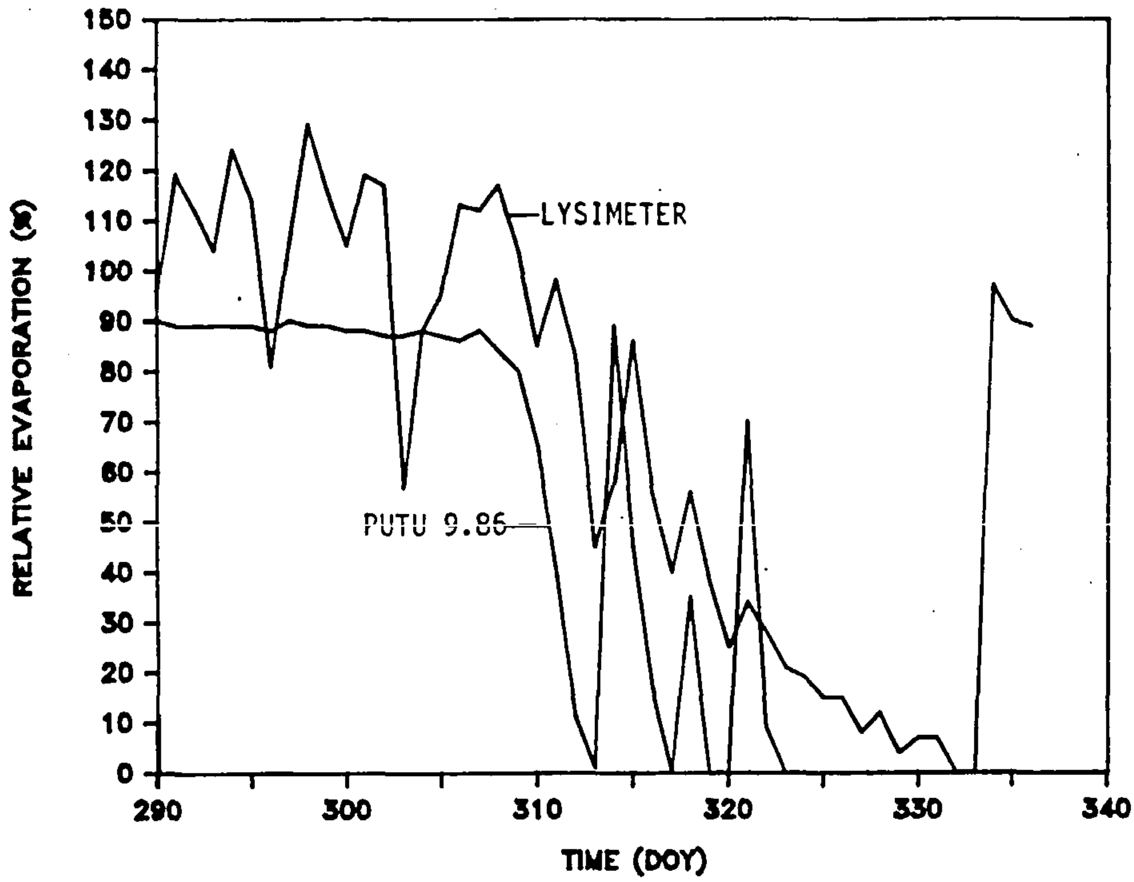


FIG 7.3a - Scenario of lysimetrically measured and relative total evaporation simulated using PUTU 9.86 during 1984.

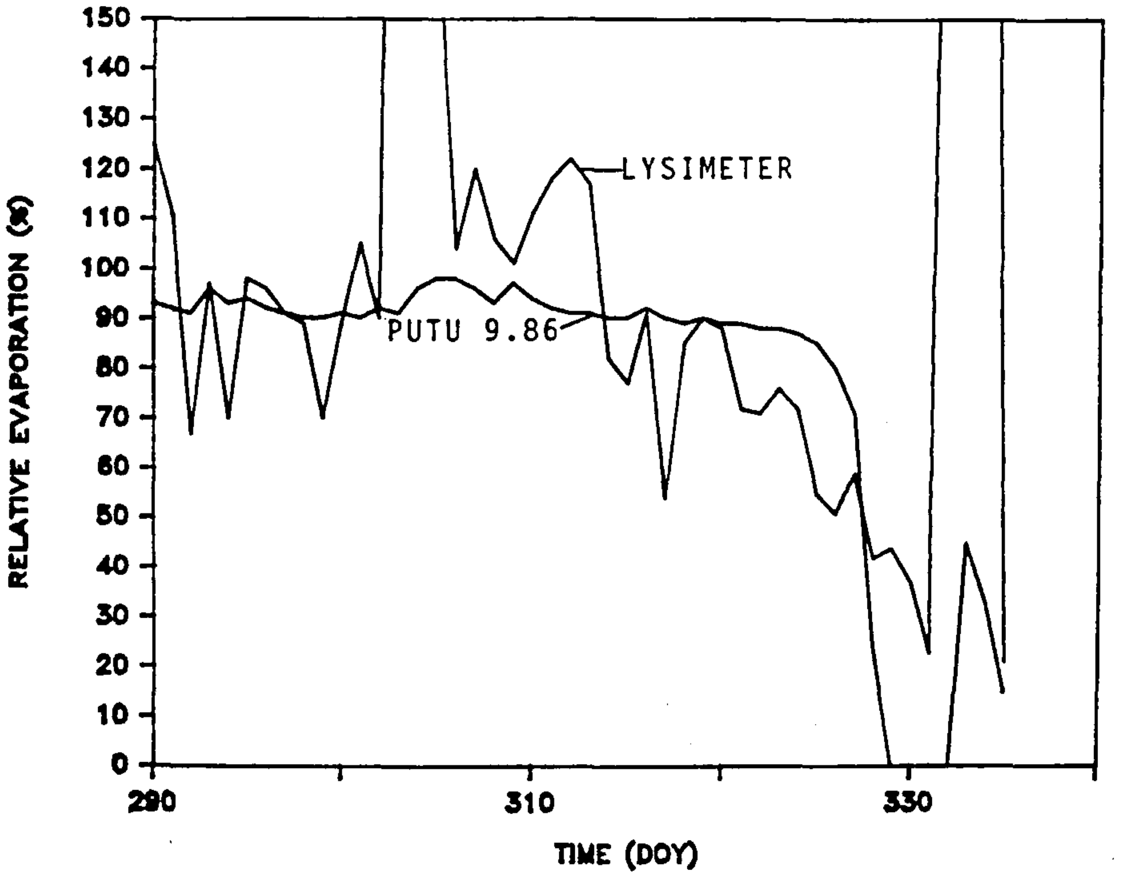


FIG 7.3b - Scenario of lysimetrically measured and relative total evaporation simulated using PUTU 9.86 during 1985.

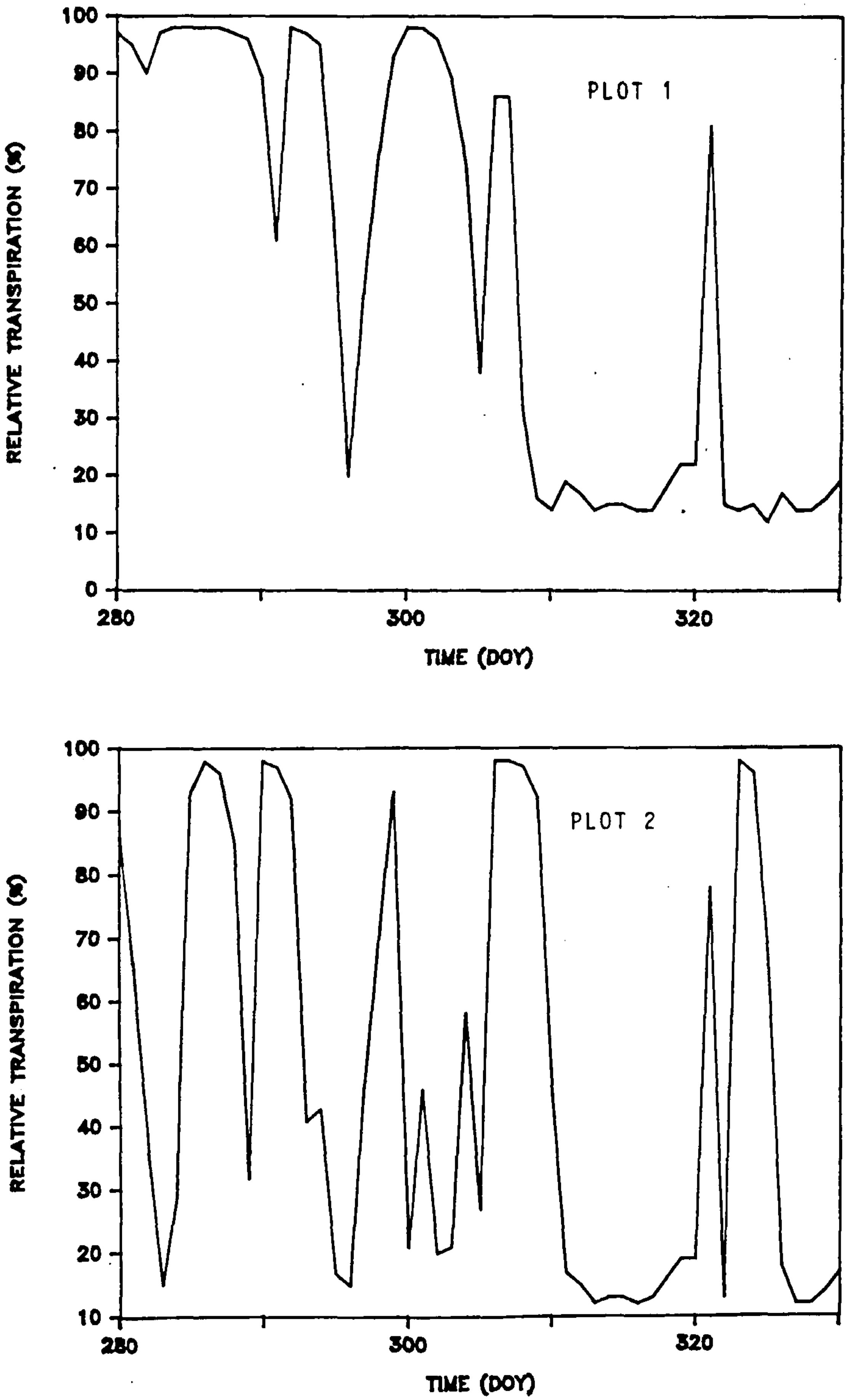


FIG 7.4 - Scenario of simulated relative total evaporation, Fh, during 1984 on Plot 1 and Plot 2.

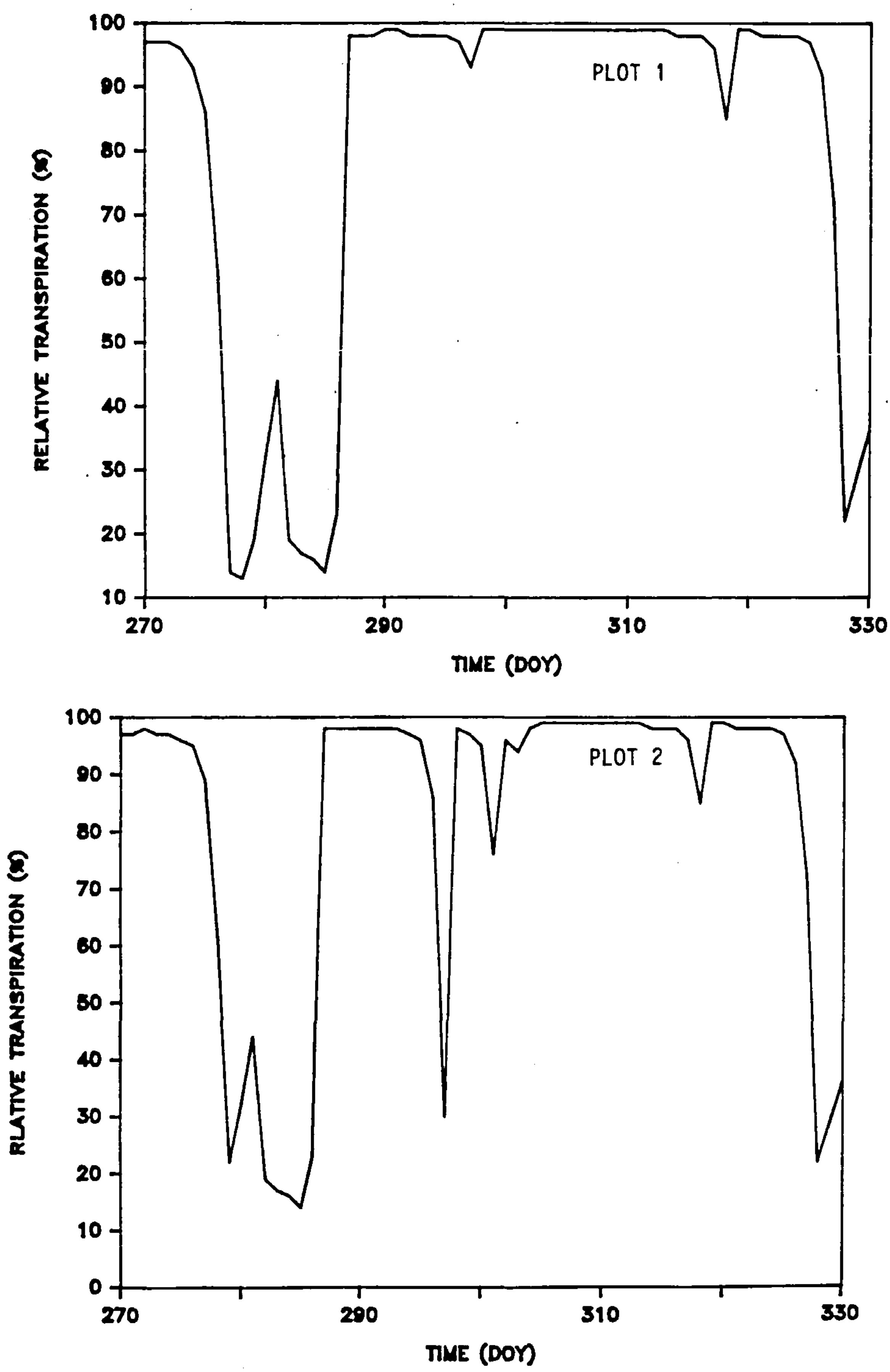
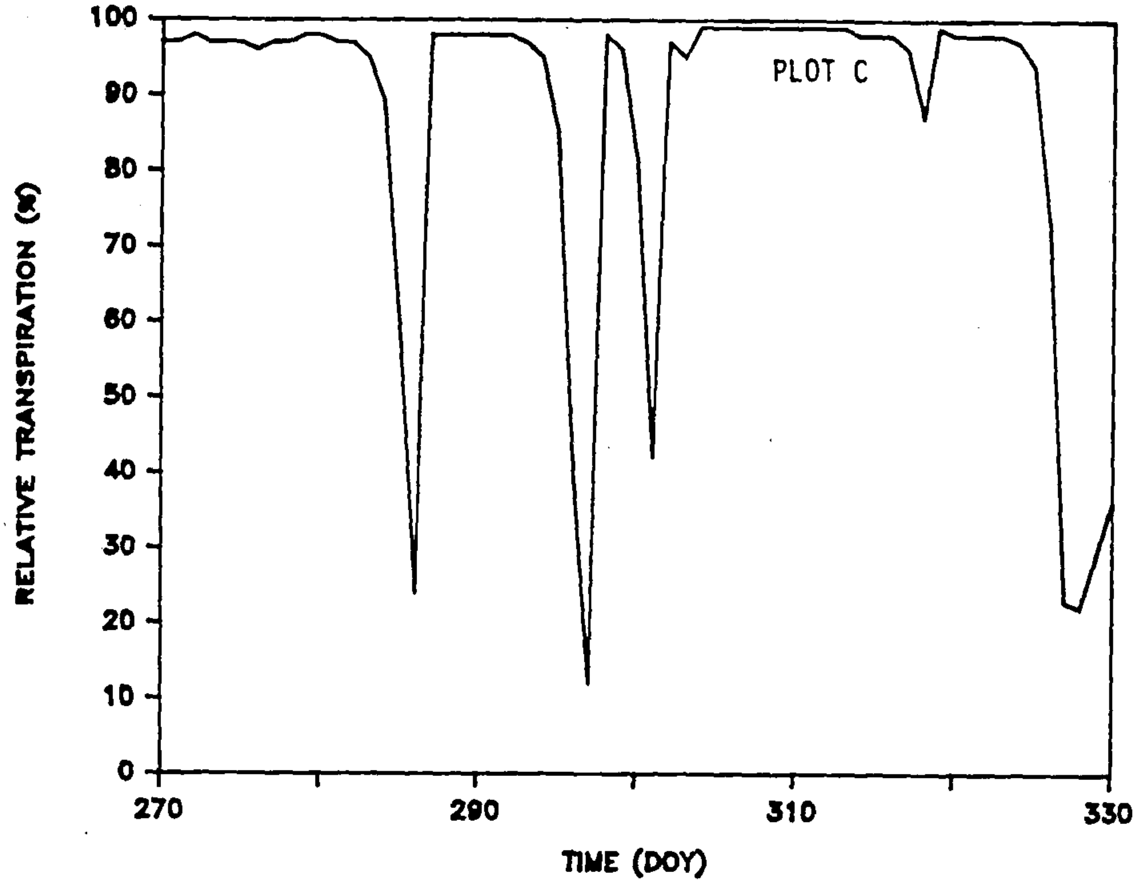


FIG 7.5 - Scenario of simulated relative total crop evaporation, Fh, on Plot 1 and Plot 2 in 1985.



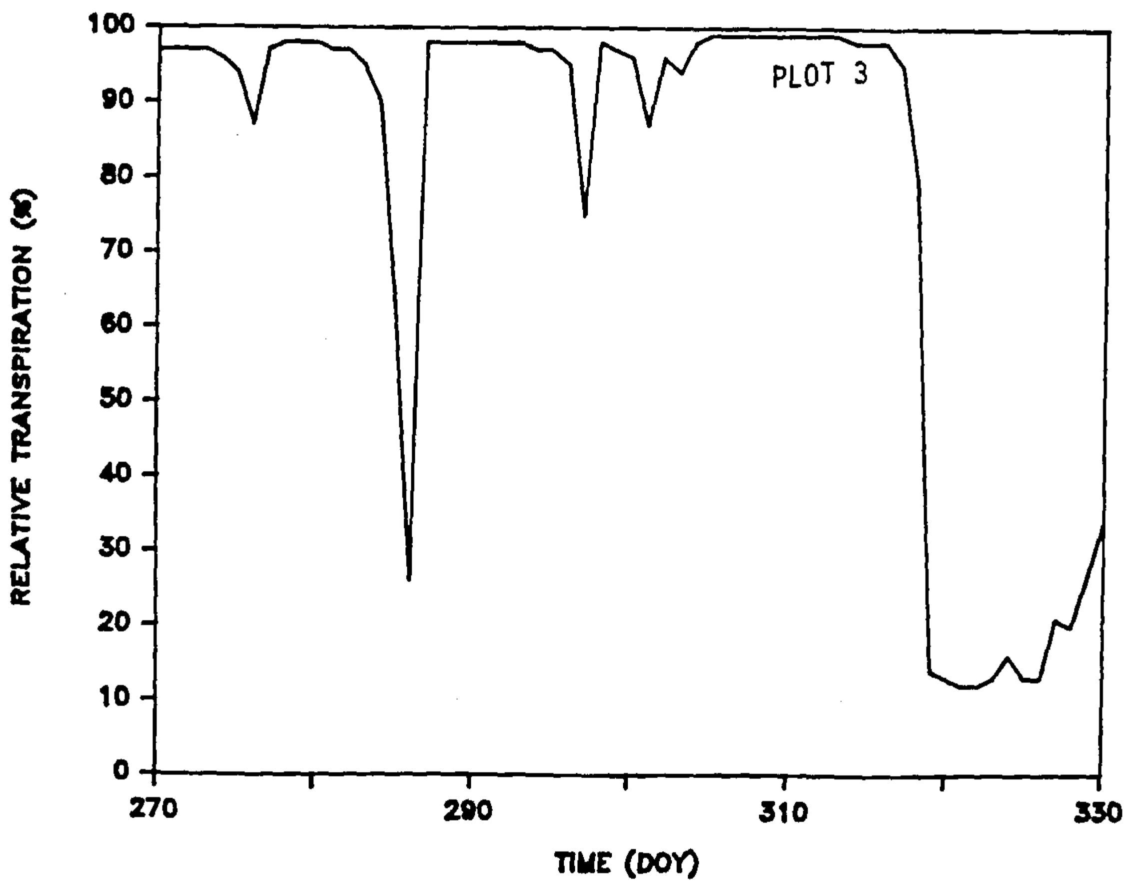


FIG 7.6 - Scenario of simulated relative crop evaporation, Fh, on Plot C and Plot 3 during 1985.

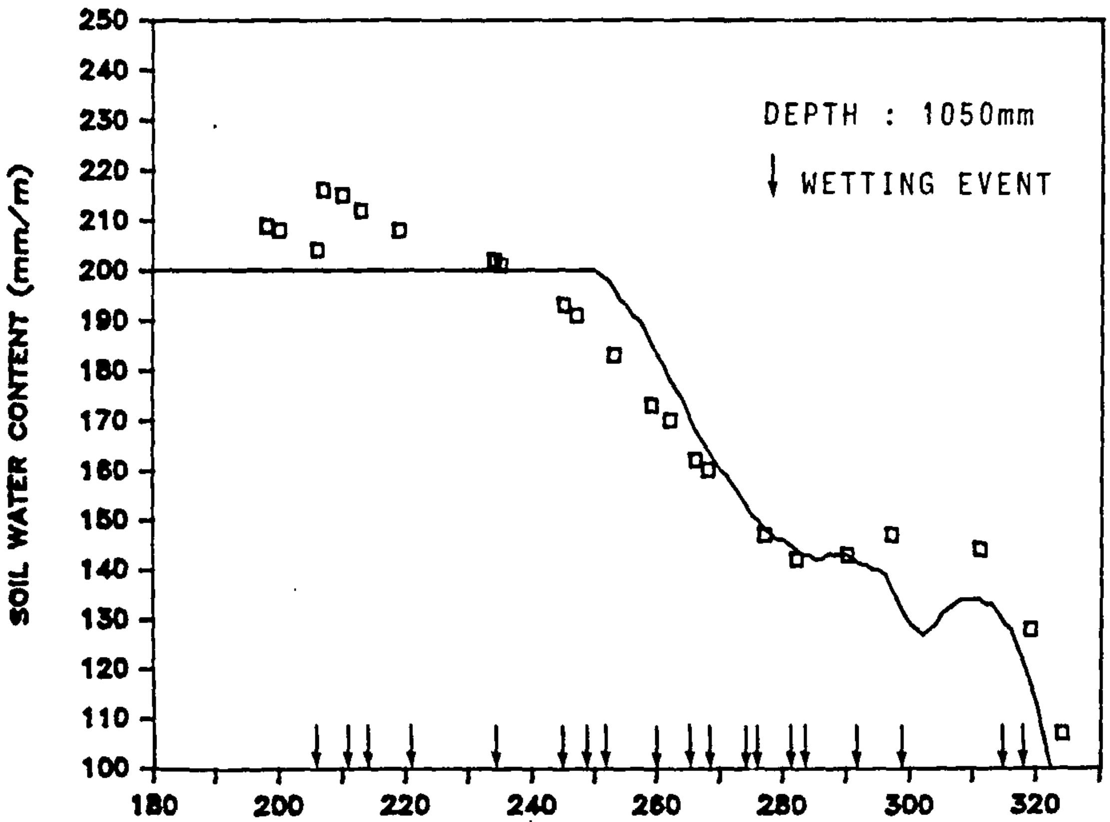


FIG 7.7 - Measured (□) and simulated (-) values of soil water content at 1050mm depth in the lysimeter during 1985.

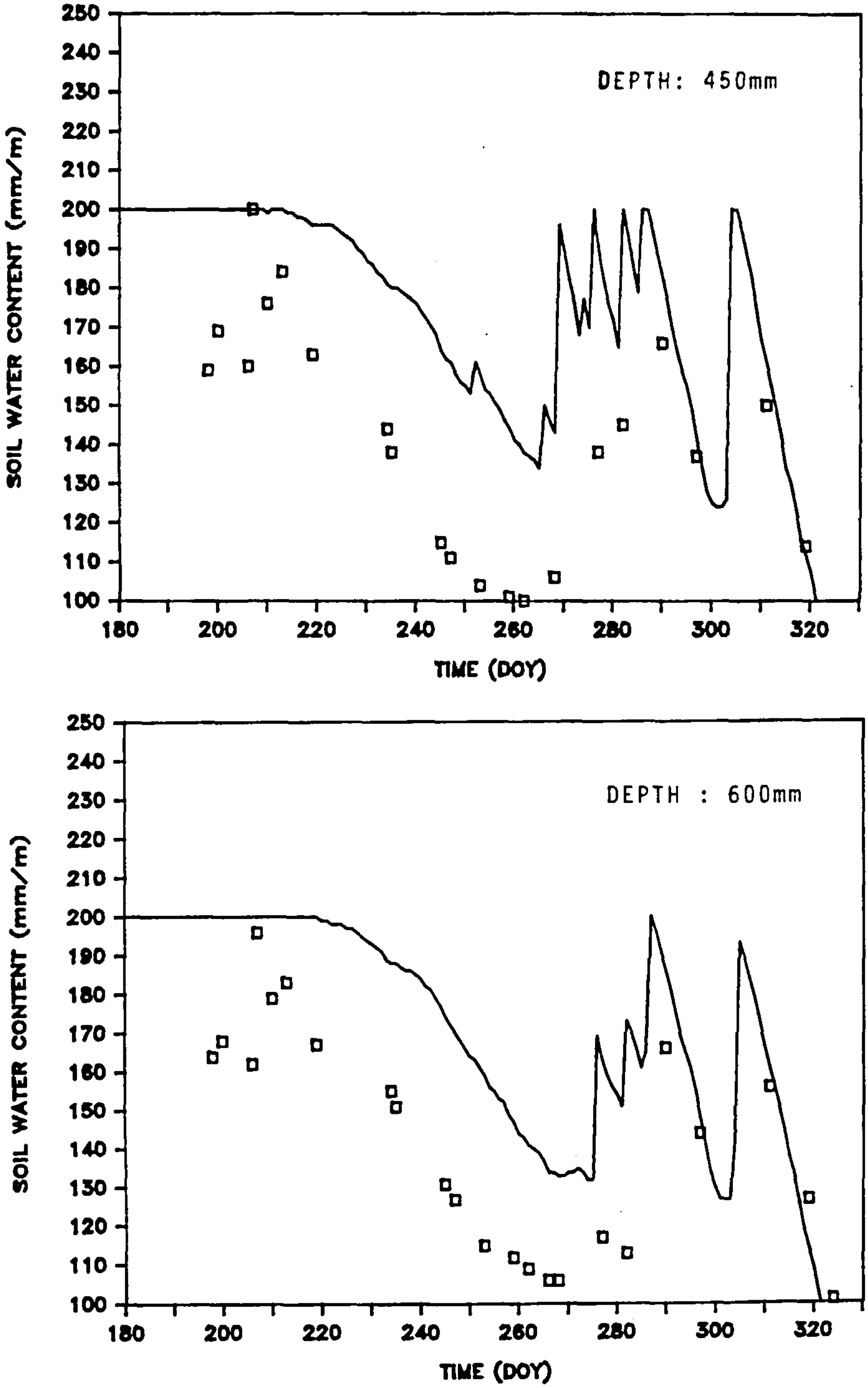


FIG 7.8 - Measured (□) and simulated (-) values of soil water content at 450mm and 600mm depth in the lysimeter during 1985.

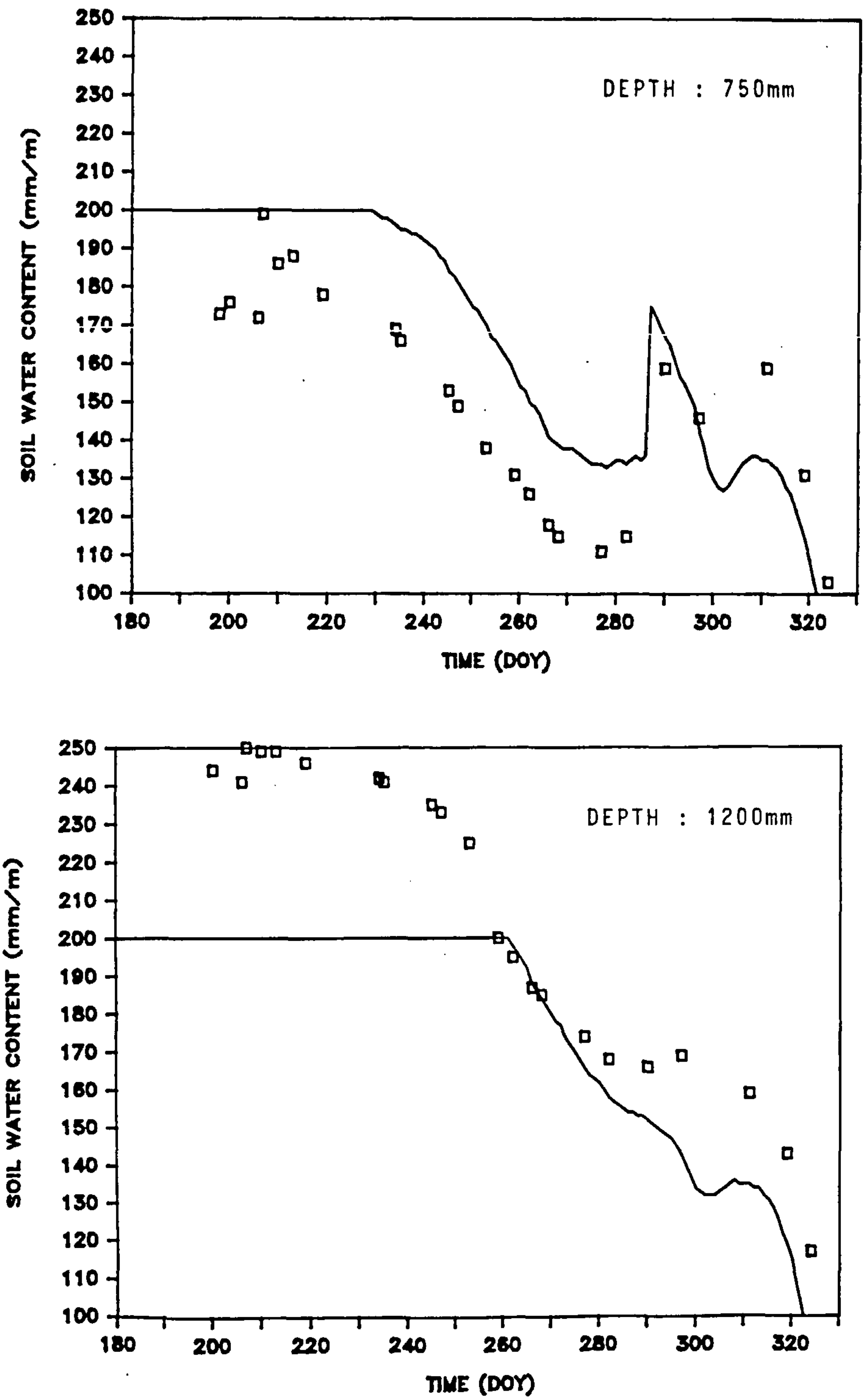


FIG 7.9 - Measured (□) and simulated (-) values of soil water content at 750mm and 1200mm depth in the lysimeter during 1985.

CHAPTER 8

THE EXPERIMENTS OF 1982 AND 1983

The objective of the cooperative experiments was to

(a) obtain experience with the running of a weather service for scheduling irrigation on farms at Hartswater,

(b) establish what type of information was required from participating farmers, and

(c) collect whatever data possible for testing the models and if possible, demonstrate the reliability of the technique.

The data collected are reported in APPENDIX X. Reference to figures or tables in APPENDIX X will be preceded by X.

METHOD

Scheduling

In 1982 the first four farmers listed in Table 8.1 assisted with the demonstrations and tests. These same four farmers were joined in 1983 by the two other farmers shown in Table 8.1. Cultivation practices adopted during both years are given in Table X.21. In 1982 preliminary tests were carried out on irrigation scheduling using weather data collected from the routine weather station installed at Vaalharts Winery Cooperative. The method in which weather data were collected is described in detail in Chapter 10 and by De Jager et al (1982).

Essentially each farmer managed his plots according to his normal practice and another set of plots on the same farm were scheduled from the UOFS. Based upon the prevailing weather and computer simulations, recommendations on when to irrigate were telephonically conveyed to the farmers. They then proceeded to irrigate according to their normal practice.

Due to the severe drought of 1983, the supply of irrigation water to all the participants, except for Site F in Bultfontein, was drastically rationed. Farmers were able to utilize only approximately one half of their irrigable land.

Field observations

Monitoring of plant growth and soil water took place at weekly intervals at Site A and B in 1982 and 1983. Leaf water potentials were obtained using the Scholander pressure chamber. Predawn and noon observations were taken on eight leaf samples. Simultaneously, leaf area indices were determined from 0,5 m long, in-row, destructive samples. The total leaf area of each sample was determined using an optical leaf area meter. Furthermore, gravimetric soil water measurements were made in the 0-300, 300-600 and 600-900 mm soil layers. Seven replications were taken at each level. In 1983 the gravimetric measurements were also carried out at Site F. The only observation made at all four sites in 1982 and 1983 was that of crop height.

In 1982 each participant provided three irrigation plots of the size shown in Table 8.1. All monitoring of plants and soil was done in the middle plot. At the end of the season, ten samples of yield within a 1 m x 1 m square wire frame were obtained. Samples were taken at 10 m intervals down the length of the plot; except at Site B, where 20 m intervals were employed. The frame was positioned randomly at the prescribed distance. Neither were bad patches avoided nor good patches sought. The same procedures were carried out on the centre plot of the closest three plots controlled by the farmer. The cultivation practices adopted during 1982 are as shown in Table X.21. In 1983, fifteen yield samples were taken on each plot instead of the ten utilized during 1982. Furthermore, samples were extracted from random locations in each plot.

At Site F (Bultfontein) soil water conditions were merely monitored throughout the growing season and therefore no other comparisons were possible. Here a line move system was in operation. Weather data from the UOFS was used for the simulations at Bultfontein. The farmer provided the relevant rainfall and irrigation information.

RESULTS AND DISCUSSION

During 1983, an irrigation strategy was designed for Site A. This is described in Table 8.2. Here, the objective was to improve total production for the farm with the limited water supply. Establishing the most effective strategy remains a manager's major problem. Hence, it was decided that this matter was deserving of special attention. Building on the strategy outlined in Table 8.2, a theoretical solution is provided in Chapter 12.

The wheat grain yields obtained in the 1982 season are given in Table 8.4a. Yield losses due to the experimentation were marginal and none of the farmers requested compensation.

These experiments were designed primarily to demonstrate the scheduling procedures. It was not possible to test the system by comparing yields. Assume a 10% coefficient of variation in yields on irrigation plots on a farm. What is required is an experiment designed to prove that the model and farmer irrigation schedules plots produced equal yields. To endeavour to show a 10% decrement in yield due to the computer scheduling treatment, with 80% reliability (i.e. 80% of the time) would require eighteen repititions (36 randomized plots per farm). It is not practical to undertake such trials in the actual farming situation. Hence, from 1983 onwards the demonstrations were aimed primarily at scheduling of irrigation by computer to obtain experience. As much useful information as possible on the functioning of the model was also collected.

The dates upon which irrigation took place are given in Table X.1 and X.8. For practical considerations such as labour and water availability, managers were not able to irrigate on the exact dates requested by the computer scheduling programme. Had the recommendations been adhered to, then one irrigation would have been saved at Site A in 1982 (see Table X.1). An irrigation on DOY 245 instead of irrigations on DOY 237 and 251 were recommended by the model. At Site B, the model would have postponed the irrigation of DOY 278 until later. At Site C, an irrigation on DOY 240 was recommended in place of those which eventually occurred on DOY 235 and 244. With such good correspondence between the scheduling by the farmer and the computerised technique, it is not surprising that the yields were similar. This agreement did however suggest, at this early stage, that the frequency and timing of irrigation scheduled by computer approximated that deemed necessary by the farmers. In the four trials irrigation was applied 33 times by both farmers and UOFS. Irrigations were scheduled simultaneously on 82% of the occassions.

The hydraulic crop factor, Fh, was used for scheduling irrigation. Fh is defined as the relative vegetative evaporation rate, i.e. Ev/Evm. When the value of Fh dropped below approximately 80%, irrigation was recommended. A forecast of Fh for the ensuing week was obtained by inputting the previous week's weather data commencing with the current soil water content and leaf area index as determined by the time of the immediate previous computation. The values of Fh obtained during the 1982 season are given in Fig. X.7. It is evident from this figure that theoretically water stress had occurred.

In Fig. X.14 through X.18 the scenario of Fh for the 1983 season at four sites is given. At Site F (see Fig. X.20b), a policy of maintenance irrigation was practised. The area under irrigation was too large to meet atmospheric evaporative demand required to ensure maximum yield. Hence, a steady decrease in mean root zone water content was expected as the season progressed. This is evident from Fig. X.20b. Monitoring of this experiment, provided valuable experience in the scheduling of line move irrigation systems and illustrated the results of poor irrigation planning.

Results describing the water dynamics at Site A and Site B in 1982 and 1983 are given in Table X.2, X.9 and X.10. Statistical tests on the data are reported in Table 8.3. The lack of agreement (low SI) between calculated and measured water use at Site A gave cause for concern. It could have been caused by upward movement of water from a water table. It was most probably due to errors in the gravimetric technique. The results from Site B however, were reassuring. These results emphasized the need for the model to be tested against the lysimeter measurements.

Leaf area index measurements for the 1982 and 1983 seasons are illustrated in Fig. X.4 and X.12. Only at leaf area indices less than three does the leaf area sub-model play a significant role. At leaf area indices higher than three, evaporation from the crop, Ev, approaches maximum total evaporation Em. These results were not as favourable as those obtained by De Jager et al (1982) and hence indicated that the leaf area sub-model needed refining.

A simulation index SI (Willmott, 1982) of 0,7 is generally accepted as an indication of acceptable reliability when modelling biological processes. The SI-index for 1982 and 1983 given in Table 8.4c suggest that (with the exception of Site A in 1982) the original leaf area sub-model was acceptable. Further development and validation of this sub-model was undertaken. The results are reported in Appendix III. The SI, r and MAD (mean absolute difference) obtained of ,97, ,83 and ,12 respectively, indicate that the revised sub-model was sufficiently accurate.

Noon and pre-dawn measured and simulated leaf water potentials are presented in Fig. X.6 and X.13 plotted from the data in Table X.5 and X.11. It is evident that simulated values under estimated actual potentials (taken positive) at pre-dawn. At noon, measured leaf water potential exceeded simulated values, taken positive, suggesting the need for refinement of the leaf water potential model.

The poor performance of this sub-model during 1983 could have been due to the generally dry conditions brought about by the water restrictions applied during this time. These circumstances precipitated the desire to improve PUTU 9 and resulted in the creation of PUTU 9.86.

During 1983 stressed conditions probably prevailed for a good proportion of the time. This provided a critical test of the leaf water potential sub-model. The model consistently underestimated noon leaf water potential by approximately 8 bar.

It is apparent that simulated pre-dawn leaf water potentials were also lower than corresponding measured values. This could have been due to the spline functions utilized to describe the soil water desorption curve. Underestimation of soil water potential could have caused the error. An improved desorption curve was subsequently included in the model (see Chapter 4 and APPENDIX I). The crop hydraulic conductance in PUTU 9 also appeared to be too high. This sub-model was also modified later (Chapter 4).

It was concluded that the leaf water potential sub-model of PUTU 9 functioned inaccurately. Much of the error could probably be eliminated by decreasing the crop hydraulic conductance. The nature of the water stress factor however, still produced reasonable simulations of the onset of crop water stress.

Tests on the soil water sub-model

The results of monitoring water use at Site A, B and F are given in Table X.2, X.9 and X.10. It must be borne in mind that gravimetric samples could only be taken to a depth of 0,9 m. At Sites B and F roots reached depths considerably greater than this. Plant available soil water content may be expected to increase with depth in the root zone of wheat due to decreasing root density. Hence the gravimetric sampling probably underestimated soil water in the total root zone. Most of the water extraction required for supporting crop growth takes place in the second soil layer of the model which occurred between 0,1m depth and the simulated depth of the effective root zone. Hence most attention was focussed upon the volumetric soil water contents in this layer (θv_2). Little water (approximately 12 mm) is present in the top soil layer for only short periods. Hence, the effect of errors in this layer in this type of model is minimal.

The results listed in Table 8.4c for 1982 show that the model accurately simulated θv_2 While, this result includes a spurious correlation due to the common dependence of both simulated and measured values upon simulated effective rooting depth, such temporal increase in soil water in this layer does constitute a real natural phenomenon. Hence the 1982 θv results should not be ignored. The 1983 scenario of soil water content are illustrated in Fig. X.19 and X.20. The agreement between measured and simulated values is not as good as was expected. It is however, interesting that after DOY 240, when a full vegetative canopy prevailed, the agreement is better than early in the season at Site A. It is unlikely that crop water stress occurs early in the season when roots have the capability of growing into wet deep root zones diminishing the consequences of a poor model in this stage. Measured soil water content was underestimated as is clearly evident from these figures. These discrepancies emphasize the urgent need for accurately determining maximum soil water content. In particular, had the field water capacity at Site B in 1983 been assumed lower, exceptionally good agreement between measured and simulated values would have resulted.

It is apparent from Fig. X.20 that management at Site F selected too large an area to irrigate. The result was that the second root zone progressively dried down as the growing season developed. The applications of approximately 6mm of water per irrigation event were insufficient to accommodate daily atmospheric demand.

From the above information it was concluded that an accurate determination of the field water capacity is essential at any site at which the model is to be applied. Furthermore, relevant SI values in Table 8.3 suggest that apart from Site B in 1983, where something obviously went wrong, the soil water sub-model performed reasonably. Model input data were too few for conclusions to be drawn about Site F.

These results reflect that much water stress occurred due to the limited supply of irrigation water. The Fh-index scenario illustrated particularly well the gradual depletion of soil water at Site F (see Fig. X.20c). The simplicity with which crop water stress may be identified with this index is self-evident.

The number of stress days identified by the model at each site are given in Table 8.5. There is poor agreement between number of stress days and yield. This is to be expected as the adjustments in yield reduction coefficient (ky in Chapter 3) with age have not been taken into account.

The variability in gravimetrically determined soil water content was deemed too large to provide measurements against which to test the water use model. This is true particularly when samples have to be collected and transported to a destination 250 km distant. It was therefore decided to reserve model testing for the West Campus Site and concentrate on establishing and standardizing the most effective modus operandi for running a computer based scheduling service using the field investigations.

TABLE 8.1 - List of participants in the field demonstrations and tests of 1982 and 1983.

SITE	LOCATION	DEPTH OF WATER TABLE	IRRIGATION PLOT SIZE	IRRIGATION SYSTEM
		(m)	(m)	
A	Hartswater	1,0	6 x 200	Flood
B	Magagong	2,3	6 x 287	Flood
C	Tadcaster		6 x 118	Flood
D	Tadcaster		6 x 90	Flood
E	Magagong		6 x 118	Flood
F	Bultfontein			Line move

TABLE 8.2 - Scheduling strategy designed to improve total farm production at Site A in 1983.

DATE	SUPPLY PERIOD NO	IRRIG. AMOUNT	IRRIGATION PLOT	GROWING STAGE	DAYS AFTER PLANTING
		(Storage unit)			
JUNE					
01	-	1/2	a		
03	-	1/2	b		
05-10				Plant	0
JULY					
14	15	1	a	Secondary roots	29
16	15	1/2	b	Secondary roots	29
AUGUST					
15	20	1	a	Start stem extention	61
19	20	1/2	b	Start stem extention	62
SEPTEMBER					
05	23	1	a	Late stem/start anthesis	83
07	23	1/2	b	Late stem/start anthesis	80
19	25	1	a	End anthesis	97
21	25	1/2	b	Anthesis	92
OCTOBER					
05	27	1	a	Soft dough	113
07	27	1/2	b	Soft dough	108
20*	-	1	a	Hard dough	128

a - Two blocks of approximately 3,2 ha each (6,4 ha)
b - One block of 3,5 ha.

* Should no rain occur, ignore the irrigations planned for 21/9 and 7/10 on b and apply one extra on treatment a (20/10).

NOTE: It may be that irrigation on 7/10/83 on treatment b will not be permitted because of the (the so-called 10% evaporation loss) further restrictions.

If Zaragosa is planted then postpone irrigation on 15/8 by approximately 7 days. Thereafter all irrigations will be delayed by 7 days because Zaragosa flowers 10 days later than does T4.

Fertilizer recommendation: a - as usual (130 kg N and 35 P)/ha
b - (100 kg N and 25 kg P)/ha.

TABLE 8.3 - Tests on accuracy of PUTU 9 for estimating water use using gravimetric soil water measurements from Hartswater in 1982 and 1983.

1982	SITE A		SITE B	
	WUSE	PAN F	WUSE	PAN F
n (#)	12		7	
a (interc)	0,39	0,41	0,85	0,79
b (slope)	9,18	0,17	10,46	0,20
Y (mean)	28,00	0,54	60,14	1,06
r (correl)	0,61	0,65	0,62	0,55
SI	0,60	0,58	0,77	0,72
MAD	21,50	0,40	6,29	0,17
MAD/$\bar{Y}$	0,77	0,73	0,10	0,18

1983	SITE A		SITE B		SITE F	
	WUSE	PAN F	WUSE	PAN F	WUSE	PAN F
n	10		7		4	
a	0,71	0,86	0,29	0,42	0,15	0,99
b	4,18	-0,03	19,95	0,33	32,32	0,45
Y	35,06	0,59	28,26	0,56	36,27	1,02
r	0,76	0,67	0,40	0,56	0,11	0,41
SI	0,85	0,76	0,64	0,75	0,40	0,32
MAD	17,52	0,31	14,20	0,25	16,10	0,52
MAD/$\bar{Y}$	0,50	0,52	0,50	0,45	0,44	0,51

Y are the measured values

SI is the simulation index of Willmott (1982)

MAD denotes mean absolute difference (measured - simulated)

TABLE 8.4a - Wheat grain yields obtained in 1982.

SITE	FARMER		UOFS	
	YIELD	STANDARD DEVIATION	YIELD	STANDARD DEVIATION
	(t/ha)	(t/ha)	(t/ha)	(t/ha)
A	5,4	0,9	5,0	0,9
B	7,6	0,8	6,8	1,0
C	6,8	0,8	6,8	0,6
D	4,2	0,5	3,7	0,7

TABLE 8.4b - Wheat grain yield and standard deviations obtained on the Experiment, Whole Farm and Control plot sites in 1983.

SITE	UOFS		FARMERS		
	EXPERIMENT	STANDARD DEVIATION	WHOLE FARM	CONTROL PLOT	STANDARD DEVIATION
	(t/ha)	(kg/ha)	(t/ha)	(t/ha)	(kg/ha)
A	3,10	615	4,20	4,14	756
B	5,35	1 341	5,30	6,97	643
C	6,60	610	2,70	5,27	823
D	5,12	430	5,40	6,08	489
E	4,23	1 039	6,10	4,89	675
MEAN OF ABOVE	4,89		4,74	5,48	
F	4,35	201	4,13		

TABLE 8.4C - Statistical reliability tests carried out on PUTU 9 during 1982 and 1983.

YEAR	SITE	VARIABLE (VAR)	r^2	RELIABILITY INDEX (SI)	MEAN DIFFERENCE	MEAN OF ABSOLUTE DIFFERENCE (MAD)	$\frac{MAD}{MEAN}$ X 100 (%)	MAX ABSOLUTE DIFFERENCE
1983	A	LAI < 3	0,91	0,82	0,37	0,5	52	1,6
1983	B	LAI < 3	0,59	0,83	-0,40	0,6	32	1,2
1982	A	Noon leaf water potential (bar)	0,22	0,50	-2,30	3,9	24	8,8
1982	A	Pre-dawn leaf water potential (bar)	0,71	0,71	-2,42	2,5	55	4,6
1982	B	LAI	0,42	0,71	1,63	1,7	40	5,2
1982	A	LAI	0,23	0,62	1,38	2,1	60	6,1
1982	B	Noon leaf water potential (bar)	0,03	0,36	-2,67	4,9	29	10,2
1982	B	Pre-dawn leaf water potential (bar)	0,10	0,55	-2,03	2,8	68	6,0
1982	A	$\theta v2$ (mm layer^{-1})	0,71	0,84	27,40	30,0	26	69,0
1982	B	$\theta v2$ (mm layer^{-1})	0,94	0,98	1,20	7,4	7	43,0
1982	A	$\theta v1$ (mm layer^{-1})	0,02	0,41	5,20	6,8	65	21,0

TABLE 8.5 - Showing the number of theoretical stress days experienced and yields measured during 1983.

SITE	UOFS		FARMER	
	YIELD	STRESS	YIELD	STRESS
	(kg/ha)	(d)	(kg/ha)	(d)
A	3,1	14	4,2	5
B	5,3	8	5,3	8
C	6,6	34	2,7	28
D	5,1	16	5,4	11
E	4,2	32	6,1	22

CHAPTER 9

THE EXPERIMENTS OF 1984 AND 1985

OBJECTIVE

The objective of the work was to obtain experience in scheduling irrigation for a number of farmers using computer simulation model and weather input data. From the experience gained, the best procedure for managing an effective service was standardized.

PROCEDURE

In 1984, farmers at Hartswater made available 19 plots to assist with the experiments. A list of the experimental sites is provided in Table 9.1.

Participants were advised that they would be provided with a forecast of the date when irrigation of their plots had become necessary. The final decision on when and how much to irrigate however, remained their responsibility. In view of the cuts in water supply during 1984 it was deemed inadvisable in any way to interfere with participants' farming practice.

Mr Japie Smit kindly agreed to irrigate one entire plot at weekly intervals to ensure that no stress occurred on it and Mr Van Wyk also agreed to irrigate a small plot (10 m x 10 m). When possible, comparisons between infra-red temperature on these and the normal plots were made (see Table 9.2). Air temperatures registered by the IRT were inaccurate, because of poor exposure of the bead thermistor. Hence the foliage-air differences (DIFF) reported in Table 9.2 are unreliable. The Smit plot served to determine the approximate maximum yield which might be expected under optimal irrigation at Hartswater. Yield determinations were undertaken using fifteen repetitions per plot from a 1 m^2 area on these two farms. Mean yields were obtained for the entire farm on the other sites. The results are reported in Table 9.3.

In July, 1984 an automatic weather station was erected on the meteorological site at the Vaalharts Agricultural Cooperative and data was collected weekly on a magnetic tape cassette. In 1985 the telemeterized automatic station was commissioned (see Chapter 10).

An intensive programme on a few farms was conducted in 1985. The objective was to carefully monitor operations on just six sites. The six experimental sites chosen are shown in Table 9.8.

RESULTS AND DISCUSSIONS

It became evident that certain information pertinent in each site and the cultural practices adopted were required to ensure an effective scheduling operation. An example of the details for farmer Japie Smit is given in Table 9.4.

The PUTU 9 model was used to simulate the water dynamics of the situation. Initially, weekly projections were made (Table 9.5) and the information distributed. Subsequently, the procedure had to be modified and computerized in order to save time. A typical listing of the weekly advisory from PUTU 9 upon which scheduling projections were based is given in Table 9.6.

The few IRT observations made on the farms of Japie Smit and P. van Wyk are reported in Table 9.2. In all cases the foliage of the wet plot was cooler than the surrounding wheat.

PUTU 9 was re-coded in GW Basic for use in IBM compatibles. This version was utilized subsequently.

Scheduling technique

At the onset the procedures of 1982 and 1983 were adopted in 1984. Here irrigation events were forecasted by running the model for the forthcoming week using the immediate past week's weather data. However, this absorbed excessive computing and personnel time. Prognoses of the earliest date on which irrigation would next be required were thus made by dividing the estimated soil water extraction remaining before water stress would occur by the estimated mean daily total evaporation for the ensuing period (see Meyer and Green, 1981). Estimates of mean total evaporation for the relevant crop growth stage were obtained from the previous experiments in this project. It is recommended that columns "VOLGENDE BESPROEIINGSDATUM" and "REDE" should be added to Table 9.6.

Weather data and information collection was performed and the model simulations proceeded most satisfactorily. The large number of experimental sites and the big volume of data manipulated, however, became unmanageable. This was true of computing time and the man-hours available to the project. This situation will also cause concern in an extensive advisory programme. It was therefore decided to alter the procedure and group sites by soil type and planting date. Thereafter it was necessary merely to simulate daily maximum wheat crop evaporation, Em, for each category, rather than for each plot. This cut computing time considerably.

The different categories of soil and cultivation practice used, is as follows:

SOIL TYPE	CATEGORY	PLANTING DATE	CATEGORY
Fine Sand	G 1	06/1-9	P 0
Loamy Sand	G 2	06/9-14	P 1
Sandy Loam	G 3	06/15-20	P 2
Sand Clay Loam	G 4	06/21-30	P 3

Thus, each week the daily Em was computed for each category using PUTU 9. The Em data series for a category was then filed on discette. A separate file was created for each group.

New programmes EREF and REGISTER (see APPENDIX V and VI), were written to use these files. REGISTER computed the soil water extraction and stress situation on each specific plot. An example of the listing produced by REGISTER is given in Table 9.6. These results were then used manually for prognosis of the irrigation date included in Table 9.5. The reason for each scheduling decision was always explained. These explanations were coded as follows:

R - refill the root zone with water for strategic reason (eg. secondary root development, utilisation of dam storage, etc.)

S - refill because of the danger of water stress

An indication of the limits of the categories into which the farms in this particular study were divided is evident from Table 9.1.

Data was initially transmitted telephonically to the secretary of Mr Hugo Hamman (Chief Extension Officer, Department of Agriculture, Vaalharts). Farmers were requested to call weekly to obtain the advice contained in Table 9.5. Since each farmer is expected to order water (i.e to re-fill his storage dam) from the bailiff on a Wednesday; the projections were made available by noon each Wednesday.

Farmers' response however, was disappointing. Managers preferred to follow their own irrigation scheduling procedure. It is evident that should such a system be implemented, it will have to be preceded by an extensive public relations exercise. Consideration will have to be given to providing telephonic advice directly to individual farmers. When the price of water increases and economic pressures become critical; then will managers be more circumspect than is the case at present. An education and water use efficiency awareness campaign should be an integral part of an irrigation service.

The need for grouping stations could fall away should a large, fast computer be dedicated solely to the weather based scheduling operation. The method of predicting future needs by projecting the previous weeks' weather data into the future would then be quite practical. Alternatively, individual farmers could be provided with daily Em values which they could apply in their own personal computer or calculator. The latter would certainly cultivate interest in, and awareness to, saving water.

<u>Nature of advice</u>

Farmers are keen to know how effectively they operate. Hence some form of monitoring of their performance is most valuable.

The best form of monitoring, apart from the weekly advisories, is by graphical presentations. Managers appreciate regular scenarios of:

(a) The irrigation need index, Fh, which is basically relative vegetative evaporation (transpiration) defined by

$$Fh = Ev/Evm$$

There are numerous examples of such scenario throughout this thesis (Fig. X.7, X.14 through X.18, and Fig. 7.2, 7,4 through 7.6).

(b) Leaf water potential - see Fig. 9.1.

(c) Deep percolation out of the root zone - see Fig. 9.2.

At the conclusion of the 1985 season, an analytical summary of the type shown in Table 9.7 generated acute interest and proved most significant.

SUMMARY

The summary to this chapter has particular significance to the operation of a weather service for irrigation scheduling. Hence it has been awarded a chapter of its own (see Chapter 11).

The automatic weather station was successfully used to provide estimates of Em suitable for the irrigation scheduling of winter wheat. Computing water requirements for individual plots was too time consuming and plots with similar soils and planting dates were grouped together. The computer software necessary and two operational procedures (single plot and groups of plots) for operating a weather based irrigation scheduling system were developed. Forecasting the next irrigation date either for a group of sites or for an individual site are possible. The distribution of the information however presents problems and deserves attention in the future. Direct telephonic communication with the farmers is recommended. Consideration should be given to a postal service. The delays however, might prove unacceptable.

Strategy

Because of the drought and resultant limited water supply, farmers were unable to utilize the entire land area on their farms. The specific question posed was how large an area should be irrigated. Careful analysis and discussion resulted in the strategy outlined in Table 8.2 for the farm of Japie Smit. Because of the seriousness of this problem an econometrical analysis was undertaken. It is described in Chapter 12. The findings provide guidance and a possible basis for advice on future irrigation planning.

Results

The automatic weather station was successfully connected via the normal Posts and Telegraph telephonic network, to the computer in the Department of Agrometeorology at the UOFS. This made possible dialling for real-time data acquisition from Bloemfontein. All the initial and technical problems in the system were successfully eliminated (see Chapter 10). Data was collected every Monday, Wednesday and Friday. The system functioned satisfactorily. The original automatic weather station was moved from Vaalharts Coöperative to the farm of Mr Japie Smit because of the personal supervision he provided. He furthermore permitted use of his private telephone and assisted with the necessary connections.

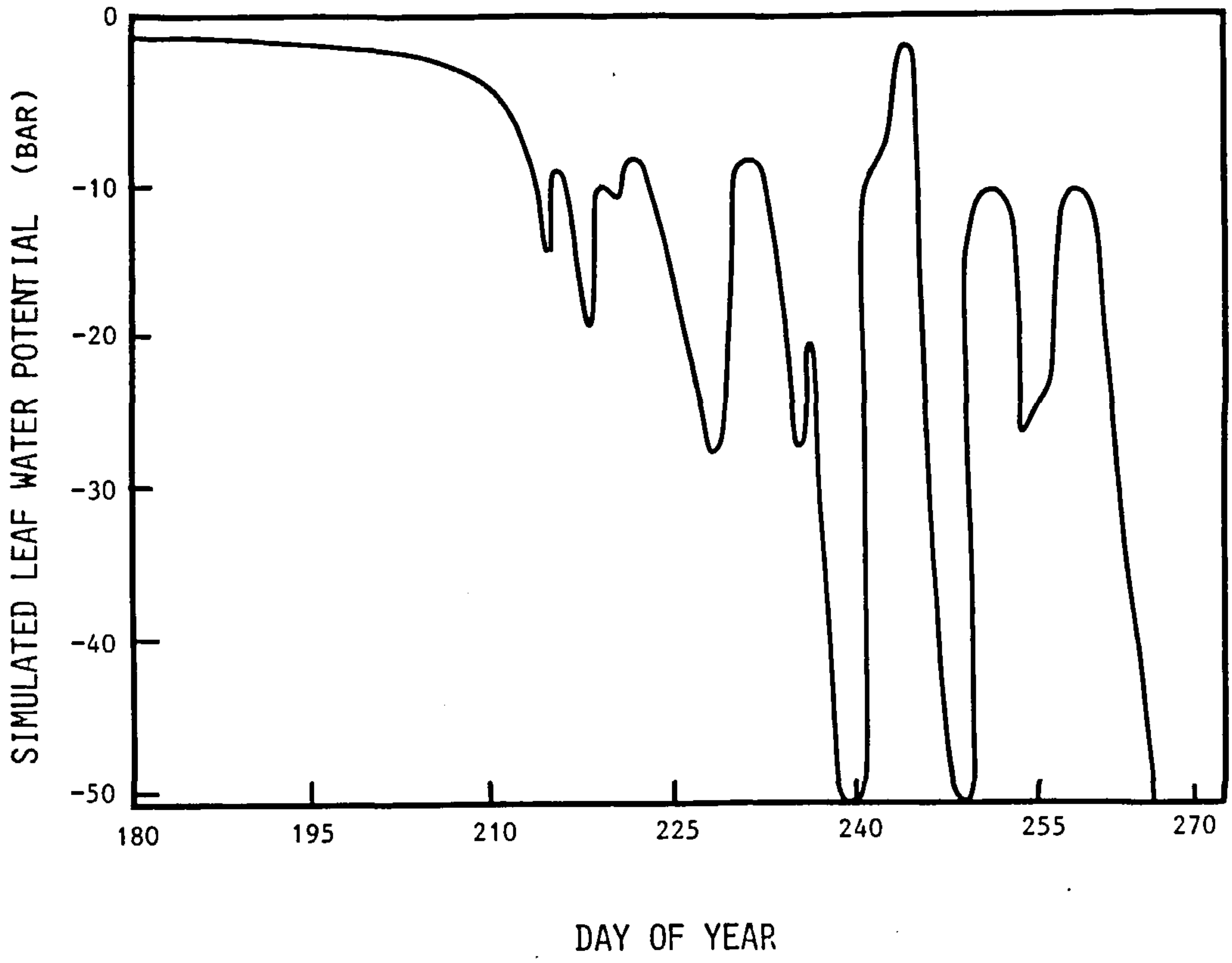


FIG 9.1 - Scenario of simulated leaf water potential at Site B during the 1985 growing season.

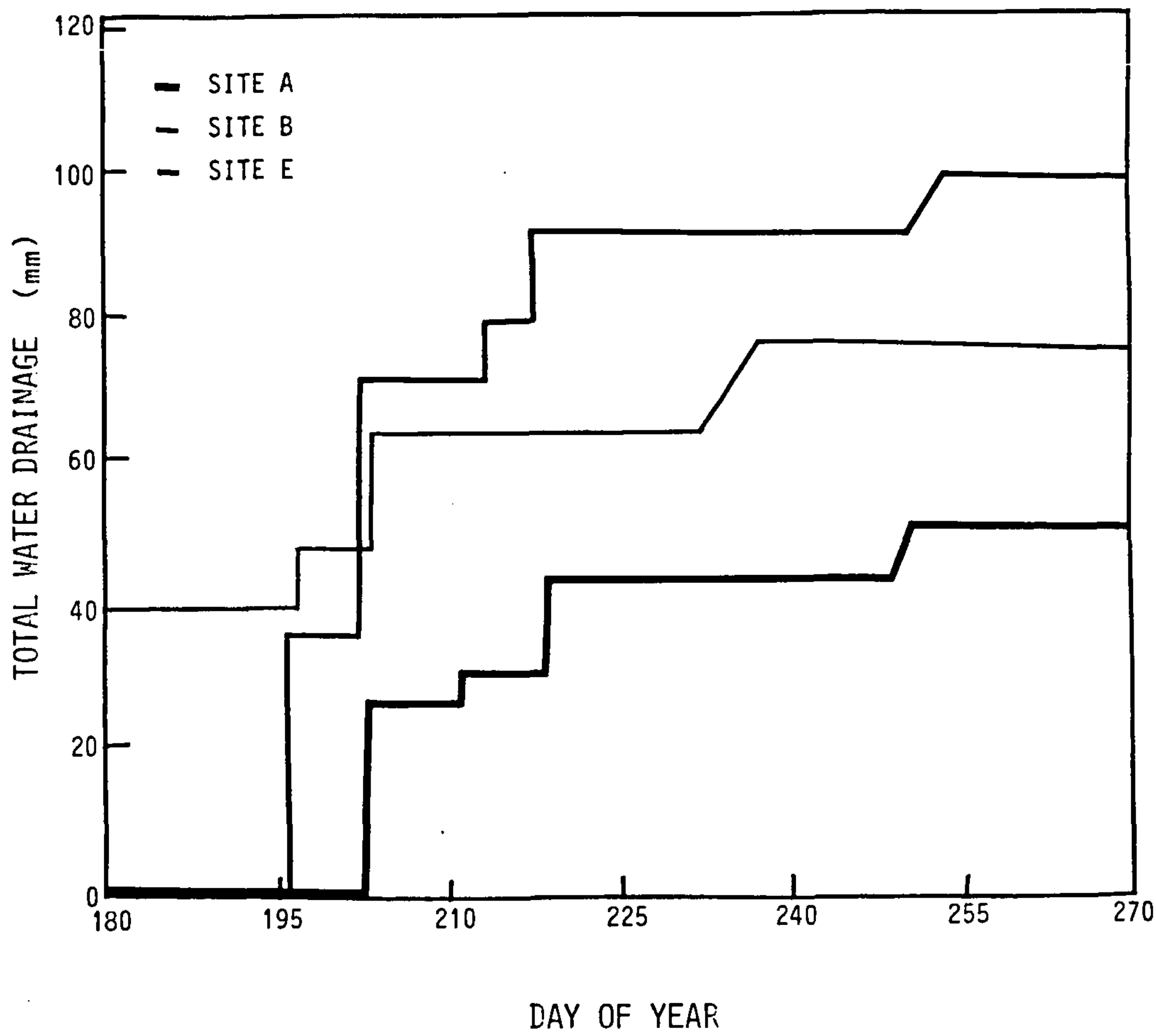


FIG 9.2 - Scenario of simulated deep percolation out of the root zone at Sites A, B, and E during the 1985 growing season.

TABLE 9.1 - Planting dates (category P) and soil physical characteristics (category G) for the various sites at Hartswater during 1984.

CAT G	CAT P	SITE IDENTIFICATION NAME	NO	PLANTING DATE	SOIL TYPE	ROOTING DEPTH MODELLED	WATER TABLE DEPTH
1	0	W VAN ROOYEN	3E6(1)	1/6/84	FINE SAND	1,3	1,5
			3E6(2)	4/6/84	FINE SAND	1,3	1,5
1	3	P VAN WYK	5C6	22/6/84	FINE SAND	1,3	1,5
			6C6	26/6/84	FINE SAND	1,3	1,5
2	1	JAPIE SMIT	E	12/6/84	LOAMY SAND	1,3	1,5+
			F	12/6/84			
		O MARITZ	5C3	14/6/84	LOAMY SAND	1,3	1+
			6C4	15/6/84	LOAMY SAND	1,3	1+
		H J VILJOEN	4C6	15/6/84	LOAMY SAND	1,3	1,5
		A G VAN NIEKERK	3B1	11/6/84	LOAMY SAND	1,3	1,5
			3B2	18/6/84	LOAMY SAND	1,3	1,5
		J HUMAN	1D6	13/6/84	LOAMY SAND	0,9	0,9
		S M HUMAN	1D5	14/6/84	LOAMY SAND	1,3	1,5+
			3D5	15/6/84	LOAMY SAND	1,3	1,5+
2	3	J L MELLET	3I3	25/6/84	LOAMY SAND	1,3	1,5+
3	1	F WOLHUTER	3M11	12/6/84	SANDY LOAM	1,3	1,5
4	1	JOHAN SMIT	JX	13/6/84	SAND CLAY LOAM	1,3	1,5+
		K STRAUSS	1E6(1)	14/6/84	SAND CLAY LOAM	1,3	1,5+
4	0	K STRAUSS	1E3(2)	6/6/84	SAND CLAY LOAM	1,3	1,5+

TABLE 9.2 - Wheat foliage temperatures (FOLIAGE) and foliage- air temperature differences (DIFF) measured by infra-red thermometer on small, well irrigated and conventionally irrigated plots on sites P van Wyk and Japie Smit at Hartswater during 1984.

	P VAN WYK				JAPIE SMIT			
DATE	WET		CONVENTIONAL		WET		CONVENTIONAL	
	FOLIAGE	DIFF	FOLIAGE	DIFF	FOLIAGE	DIFF	FOLIAGE	DIFF
840918	21,3	-5,2			20,7	-1,2	23,0	0,1
	21,9	-5,3			20,4		23,7	-0,5
	22,3	-5,2			19,2	-2,9		
841002	22,2	-7,0	23,4	-5,0	22,6	-2,7	23,8	-1,7
	21,4	-7,6	24,0	-4,0	22,6	-2,8	24,1	-1,0
	20,4	-7,9	23,4	-4,5	22,4	-2,8	23,4	-2,4
841009	17,6	-0,8	20,5	-5,7	18,4	0,9	20,7	-3,0
	18,3	-0,8	21,0	-4,9	18,0	0,3	21,5	-3,6
	18,7	-1,0	21,4	-4,9	17,5	-0,4	21,0	-3,4
	18,6	-1,1	19,8	-5,5	18,4	0,1	21,5	-3,5

TABLE 9.3 - Mean farm yields on the different sites at Hartswater during the 1984 season.

PARTICIPANTS SITE	YIELDS	COMMENTS	NUMBER OF IRRIGATIONS
	(t/ha)		
J HUMAN	6,6		9
S M HUMAN	6,6		11
J MELLET	4,93		7
O MARITZ	4,3		6
JOHAN SMIT	4,2		2
JAPIE SMIT	5,8		9
(CONTROL PLOT)	6,9	(irrigated weekly)	19
W SAUNDERS	6,3		-
A G VAN NIEKERK	5,38	18% hail damage	5
P VAN WYK	4,7		7
H J VILJOEN	3,9		7
C WOLHUTER	5,4		9

TABLE 9.4 - Details of experimental site and cultivation practices at site SMIT, HARTSWATER, 1984.

NAME OF FILE : VHS
NAME OF DISK : NICO (1)

NAME	JAPIE SMIT
FARM	BLOK E
TELEPHONE	2002 (HARTSWATER)
DATE	

SOIL CHARACTERISTICS

SOIL DEPTH	1 m			
FORM	LOAMY SAND		SERIES	
CLAY CONTENT	10 %		SILT+CLAY	12 %
FIELD WATER CAPACITY		164 mm/m		
PLANT AVAILABLE WATER		m		
WATER TABLE DEPTH		>1,5 m		
ROOTING DEPTH		1,3 m		

FERTILIZER APPLICATIONS

	TYPE 3.2.1.(25)	AMOUNT	325	kg/ha
	AMS		514	kg/ha
N	148 (BEFORE PLANTING)			kg/ha
N	25 (AFTER PLANTING)			kg/ha
P	27			kg/ha
K	13			

CULTIVAR	SARAGOZA			
SEED DENSITY	85 kg/ha			
PLANT/DENSITY	160 (pl/m)			
PLANTING DATE	840612			
IRRIGATION DATES	840604	840726	840814	840828
	840910	840924	841002	841015
	841025			

SPLINE FUNCTION FOR SOIL WATER DESORPTION CURVES

ln(ψs) (ln kPa)	θv (mm/m)
P1 = 5.94	V1 = 71.24
P2 = 5.30	V2 = 77.69
P3 = 4.42	V3 = 93.40
P4 = 3.82	V4 = 114.57

LAI ON DOY 200 = 0,5	
SIZE OF CONTROL PLOT	1/14 ha
SIZE OF PLOTS	3,5 ha
YIELD	5,6 t/ha
IRRIGATED EACH WEEK	7,1 t/ha
CONTROL	5,8 t/ha
TOTAL RAINFALL ON PLOT	64 mm
TOTAL WATER USED FOR IRRIGATION	415 mm

TABLE 9.5 - The form upon which weekly irrigation scheduling prognoses were reported.

DEPARTMENT AGROMETEORLOGY, UOFS : WEEKLY IRRIGATION ASSESSMENT

DATE OF ISSUE...........

CAT G P (1*)	SITE IDENTIFICATION NAME	NO	PREVIOUS IRRIGATION DATE AMOUNT	EARLIEST NEXT IRRIGATION DATE (2*)	REASON (3*)
1 0	W VAN ROOYEN	3E6(1)			
		3E6(2)			
1 3	P VAN WYK	5C6			
		6C6			
2 1	JAPIE SMIT	E			
		F			
	O MARITZ	5C3			
		6C4			
	H J VILJOEN	4C6			
	A G VAN NIEKERK	3B1			
		3B2			
	J HUMAN	1D6			
	S M HUMAN	1D5			
		3D5			
2 3	J L MELLET	3I3			
3 1	F WOLHUTER	3M11			
4 1	JOHAN SMIT	JX			
	K STRAUSS	1E6(1)			
4 0	K STRAUSS	1E3(2)			

1* CAT G P - The irrigation category into which the irrigation plot with the relevant Identification No falls. The soil type eg. sand is denoted by G, the planting date (see Table II.2 Appendix II) by P.

2* The earliest next irrigation date is the estimated earliest date on which it will be required to irrigate the relevant plot

3* Column three provides one of two reasons for the next irrigation :
viz. R - refill soil profile with water for a strategic reason eg secondary roots
S - danger of the onset of water stress.

TABLE 9.6 - Example of the water use advise note produced by program REGISTER using data stored by PUTU 9. "Persentasie stremming" equals (1-Fh) * 100.

WATERVERBRUIKSADVIESNOTA

W VAN ROOYEN 3E6 (1)

24/9/84 - 1/10/84

GRONDTIPE: FYNSAND

BERAAMDE WORTELDIEPTE OP DIE LAASTE DAG VAN DIE WEEK: 1300 mm

KALENDERDAG	WATERVERBRUIK	KUMULATIEWE WATERVERBRUIK	BESPROEIING	PERSENTASIE STREMMING
	(mm/d)	(mm)	(mm)	(%)
269.0	9.8	44.8	0.0	0.0
270.0	9.9	54.7	0.0	0.0
271.0	7.7	62.5	0.0	0.0
272.0	7.3	69.8	0.0	0.0
273.0	5.7	75.5	0.0	0.0
274.0	6.9	82.5	0.0	0.0
275.0	6.7	39.2	50.0	0.0

WATERVERBRUIKSADVIESNOTA

W VAN ROOYEN 3E6 (2)

24/9/84 - 1/10/84

GRONDTIPE: FYNSAND

BERAAMDE WORTELDIEPTE OP DIE LAASTE DAG VAN DIE WEEK: 1300mm

TABLE 9.7 - Analysis of irrigation scheduling which could be supplied to farmer at the end of the season.

1 Frequency of irrigation		9
2 Application per irrigation (mm)		50
3 Total water irrigated (mm)		450
4 Total water use by crop (mm)		490
5 Total evaporation through soil surface (mm)		70
6 Total atmospheric evaporative demand (mm)		934
7 Total deep percolation out of root zone (mm)		120
8 Total rainfall (mm)		40
9 Water supplied to farm (mm)		500
10 Efficiencies of :		
Irrigation management	[(3+8-7)/(3+8+14)]%	63
Water use	[4/(3+8+14)]%	83
Transport	[3/9]%	90
Management other than water	[12/11]%	85
11 Expected final yield (kg/ha)		5500
12 Actual final yield (kg/ha)		4700
13 Production coefficients		
Irrigation water use	[12/3] kg/(ha mm)	10
Total water use	[12/(3+8-15)] kg/(ha mm)	12
14 Initial soil water content (mm)		100
15 Final soil water content (mm)		100

TABLE 9.8 - The six sites used during 1985.

SITE	CLAY	SILT & CLAY	SOIL CLASS
	(%)	(%)	
D.3d	10	12	Loamy sand
B.A.c	10	12	Loamy sand
C.A.c	10	12	Loamy sand
D.3d	18	18	Sand clay loam
B.jx	18	8	Sand clay loam
E.3m11	13	14	Loam

CHAPTER 10

THE AUTOMATIC WEATHER STATIONS

INTRODUCTION

Three automatic weather stations were installed by the Department of Agricultural Meteorology, UOFS, for routine and experimental purposes. Station #1 (DIE BULT) is located in the Departmental Observatory for routine weather observations and calibrations. It was commissioned in February 1984. In October 1983, Station #2 (WEST CAMPUS) was erected at the experimental site on the west campus for research work. Station #3 was initially deployed at Vaalharts in 1984, but was linked by telemetery system in 1985 and moved to a farm at Hartswater. In view of the nature of the information that is required from each of the stations, the sensors and data format varied between the stations. However, all three stations have the same basic components.

The data logger for the automatic weather station consisted of the basic electronics of the CR21 unit supplied by Campbell Scientific, Logan, Utah*. It was assembled as the Envirologger by Ecosystems, Pretoria*. The latter provide a convenient distribution board, lightning protection and signal conditioning for certain of the weather sensors. The environmental housing and support systems were provided by Ecosystems.

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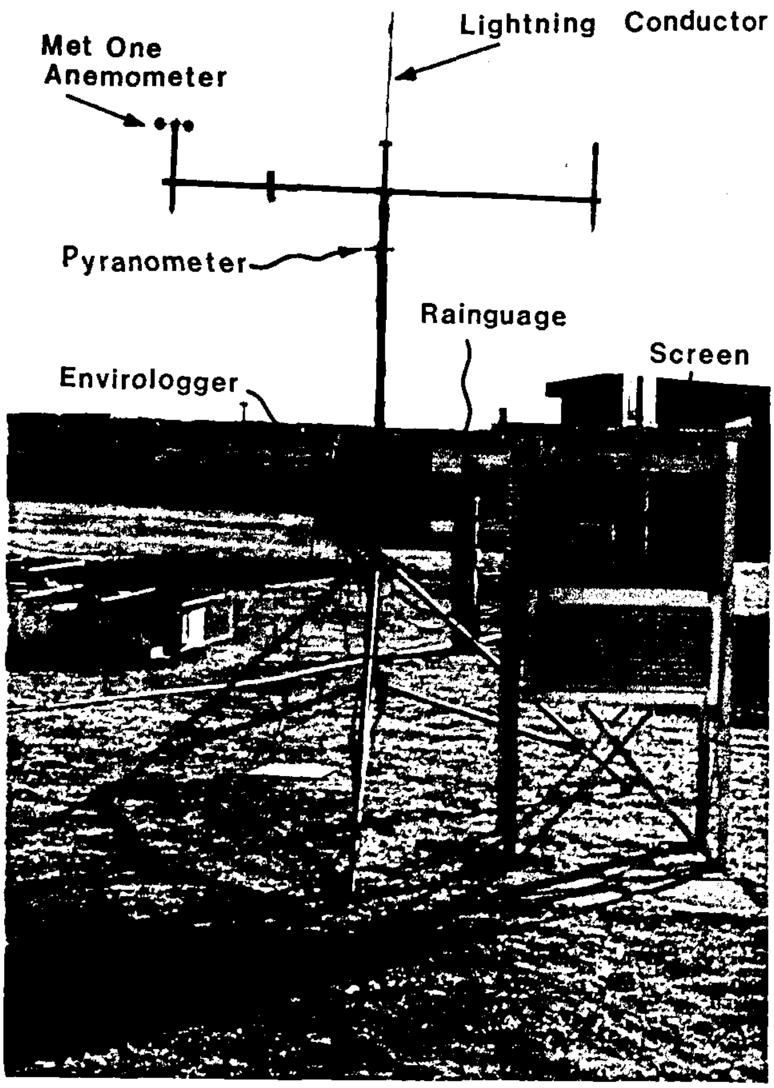
* Reference to any manufacturer, trade name or agent is for information and does not represent an endorsement by the Department of Agrometeorology, UOFS or the Water Research Commission.

FIG 10.1. The automatic weather station on the WEST CAMPUS site, showing the components common to all the automatic weather stations.



The automatic weather stations were mounted on metal tripods (Fig 10.1) with the radiation and wind sensor arm raised to approximately 3m above the ground. Each station had an environmental shelter for the temperature and humidity sensors. There is a lightning conductor (aluminium rod) mounted on the centre upright. A radiation shield protects the sealed fibreglass (Model 021) environmental enclosure in which the Envirologger (CR21) was housed. The CR21 is battery operated with a real time clock, a serial data interface, a programmable analogue-to-digital converter, and full floating point mathematics capabilities. The CR21 has a scan rate of 10s, which samples the individual sensors according to user-specified commands programmed in an input table (*4). The data is processed in a 64 location intermediate memory before final storage in a 608 word memory according to user-specified output programmes stored in three separate tables (*1,2,3). Final storage is completed only at the output intervals specified in each output Table. When the memory is fully occupied, the old data is overwritten by the new data. The memory is dumped automatically to cassette and can be accessed manually by the user.

CR21-DATALOGGER

The CR21 accepts 7 analog inputs (Channels 1-7) and two pulse counting inputs (Channels 8 & 9). Input to the analog channels are through HIGH and LOW ports. The low is common to all analog channels and is +1V with respect to ground. It is important to make sure that this port (LOW) is not earthed. The pulse channels are labelled HIGH and EARTH.

The pulse count channels have a maximum detectable frequency of 150 Hz (Channel 8) and 50 Hz (Channel 9). Each pulse must exceed 3.5V from a base of <1.5V to be detectable.

While not used in this experiment, the CR21 also has two binary inputs and four control output ports. These digital input and output ports can be used with special input and output programmes for controlling external devices (eg to turn sensors/equipment on or off).

SENSORS AND POWER SUPPLY

All three automatic stations had the following basic sensors:-

1 - LI-COR (MODEL LI200SB) SILICON PYRANOMETER
2 - 101 TEMPERATURE PROBE comprised of a Fenwal Electronic UUT51J1 thermistor encased in a water proof probe
3 - HYGROMETRIX XNAM 10205 RELATIVE HUMIDITY SENSOR and ECO MODEL XNAM/82R INTERFACE
4 - MET-ONE (MODEL 014A) CONTACT 3-CUP ANEMOMETER
5 - MET-ONE (MODEL 024A) WIND DIRECTION SENSOR (potentiometer)
6 - OSK764 TIPPING BUCKET RAINGAUGE.

The pyranometer and wind sensors were mounted approximately 3m above the ground (Fig 10.1). The temperature and humidity sensors were housed in an environmental shelter approximately 1.5m (the standard height) above the ground. The three remaining channels on the CR21 monitored different sensors at the various stations. There were periods at all three stations when data was lost. This was usually due to power failure; although lightning did cause some problems. Since the data was usually retrieved once a week, power failures did result in the loss of as much as a week of data. The problem of power failure appears to have been solved by the use of a trickle charger and regular battery maintenance.

DATA

The CR21 displays and stores a maximum value of 6999 in internal memory. The data in memory is automatically dumped to cassette tapes at regular intervals. The tapes were retrieved and the data is transfered from the cassette drive to fixed or soft disc using the Campbell Scientific Inc C-20 cassette interface and Sperry PC model 30 computer. The data was stored in files according to the following nomenclature:-

1 - Hourly mean data and daily means File = MTH-YR.STN

2 - Monthly summary of daily means File = MTH-YR.MON

where MTH = MONTH ; YR = YEAR ; & STN = STATION

station abrieviations used were = OBS (DIE BUILT)
= EXP (WEST CAMPUS)

Any alterations or corrections to the data format, usually caused by changing the CR21 programme tables, are noted at the end of each month. The GW BASIC coded computer programme (Appendix VII) checks for these corrections while listing the data in the formats shown in Table 10.1. The programme also stores the daily means or totals in a separate file (MTH-YR.MON), as well as estimates of reference evaporation (Er). These programmes differed for the different stations since the data format and necessary corrections vary between stations. However the basic structure is similar in all cases to the programme for the WEST CAMPUS station (Appendix VII).

Because of the problems arising from the necessity to correct the raw data each time, a BASIC program (Appendix VIII) was subsequently developed to make the appropriate corrections and store the data in files with the format shown in Table 10.2. These formats were chosen in order to reduce the data storage requirements. Using these formats it is now possible to store 10 months of hourly data on a two-sided double density 5.25 flexy disc, as opposed to 3-4 months with the original format.

TABLE 10.1 - Examples of a daily and monthly summary printouts.

D 259

UNIVERSITY of the ORANGE FREE STATE
Department Agrometeorology
Vaalharts

Date : 15 /SEPTEMBER/ 1984 DOY : 259

Time	Radtn W/m²	Screen Temp °C	Screen R.H. %	Soil Temp 30cm	Wind speed m/s	Wind vector m/s	Wind dirctn deg	Wind st.dv deg	Ep mm/hr	RAIN
1	-3.00	9.45	40.58	17.27	1.45	1.00	7.25	45.04	0.06	
2	-4.00	11.94	42.69	17.20	2.21	1.80	19.71	35.12	0.10	
3	-5.00	12.65	47.35	17.18	2.61	2.45	8.10	20.27	0.11	
4	-5.00	12.33	54.00	17.13	2.58	2.40	5.10	21.72	0.10	
5	-5.00	12.34	54.80	17.02	2.86	2.59	4.28	24.82	0.11	
6	-5.00	11.53	53.10	16.94	2.43	2.32	8.00	17.37	0.09	
7	22.00	11.25	64.70	16.87	2.61	2.41	353.50	22.58	0.07	
8	207.00	12.98	62.40	16.78	3.35	3.12	357.10	20.95	0.16	
9	422.00	14.52	58.80	16.71	4.29	3.98	349.60	22.06	0.43	
10	612.00	16.41	53.80	16.62	4.27	3.86	350.20	25.24	0.67	
11	754.00	18.44	48.43	16.56	4.01	3.65	346.00	24.20	0.86	
12	839.00	20.77	41.72	16.49	4.15	3.76	354.00	24.62	1.03	
13	848.00	22.47	36.96	16.41	4.23	3.87	349.00	23.64	1.10	
14	810.00	24.07	32.84	16.41	4.08	3.67	353.20	25.58	1.09	
15	625.00	24.53	30.75	16.42	4.02	3.65	1.34	24.70	0.88	
16	473.00	24.78	28.45	16.49	3.41	3.14	331.80	22.92	0.66	
17	220.00	24.33	28.33	16.59	2.61	2.42	339.00	21.89	0.29	
18	65.00	23.48	29.01	16.73	1.58	1.48	327.60	19.64	0.12	
19	-8.00	20.46	32.77	16.88	0.65	0.61	18.96	20.01	0.04	
20	-8.00	17.76	36.36	17.05	0.45	0.37	38.03	33.63	0.03	
21	-7.00	17.37	36.59	17.19	0.85	0.84	34.26	7.95	0.05	
22	-7.00	17.72	36.02	17.30	1.64	1.63	27.19	7.85	0.10	
23	-7.00	17.17	45.48	17.39	3.57	2.57	324.20	42.75	0.18	0.60
24	-7.00	14.90	64.00	17.42	1.82	1.55	95.30	31.01	0.06	
Mean	242.75	17.24	44.16	16.88	2.74	2.46	183.45	Total	8.42	0.6

Maximum Temperature 25.31 °C @ time 15.45
Minimum Temperature 6.974 °C @ time .08
Mean Temperature 17.23 °C
Mean Relative Humidity 62.16 %
Total Radiation 20.908 MJ m⁻²

WIND STATISTICS
Speed: Max 9.96 m/s @ time 22.21
: mean 2.737 m/s

WIND-DIRECTION - RELATIVE FREQUENCY(%) IN 45 DEGREE SECTORS

degrees	0 -> 45	45 -> 90	90 -> 135	135 -> 180	180 -> 225	225 -> 270	270 -> 315	315 -> 360
frequency	40.20	5.70	3.40	0.80	0.70	1.60	5.10	38.90

ghest frequency -> NNE

C- 9

UNIVERSITY of the ORANGE FREE STATE
Department Agrometeorology
Vaalharts

SEPTEMBER- 1984

Day	SCREEN max °C	SCREEN min °C	Wind max m/s	Wind mean m/s	Wind dirctn deg	RAD MJ/m²	Screen Temp °C	Screen R.H.	Ep	RAIN
1	28.44	4.72	7.96	2.21	NNW	19.53	16.14	51.26	8.42	
2	29.14	2.32	9.24	1.82	ENE	20.91	15.35	43.28	8.75	
3	23.21	4.75	9.32	2.05	WSW	18.58	13.55	47.11	7.17	
4	20.43	0.98	8.12	2.21	WSW	21.60	10.89	45.21	8.26	
5	19.97	1.44	5.81	1.61	NNE	21.60	10.22	47.91	6.92	
6	23.46	-0.36	9.32	2.00	ENE	22.03	11.50	45.01	8.87	
7	24.73	-0.90	6.61	1.27	ENE	22.03	11.49	39.88	7.29	
8	25.36	2.25	5.49	1.13	ENE	22.12	13.23	37.42	7.35	
9	22.57	-0.40	5.89	1.25	ESE	22.38	11.37	38.47	7.35	
10	25.15	0.48	8.84	1.71	ESE	21.77	14.37	43.31	8.01	
11	28.84	7.24	5.97	1.74	NNE	20.39	17.98	56.56	6.95	
12	30.15	12.15	10.12	3.04	NNW	19.70	21.17	55.78	10.00	
13	23.16	8.27	7.32	2.69	SSE	20.91	15.03	49.65	8.72	
14	21.85	0.29	5.65	1.44	WSW	22.12	10.89	56.99	6.62	
15	25.31	6.97	9.96	2.74	NNE	20.91	17.23	62.16	8.42	0.60
16	25.57	8.31	5.17	1.16	ESE	19.44	16.38	47.21	6.46	
17	27.81	4.10	5.17	1.21	ESE	22.90	15.81	41.19	7.87	
18	29.55	7.05	11.64	2.51	NNW	20.39	18.46	48.52	9.82	
19	30.03	11.66	9.00	2.60	NNW	21.86	20.40	50.18	10.24	
20	29.37	7.56	5.65	1.26	ESE	22.38	18.73	41.52	8.18	
21	33.27	8.11	8.68	1.85	NNE	22.64	20.29	43.89	9.77	
22	34.50	8.19	7.48	1.70	NNE	22.20	21.92	43.45	9.53	
23	33.34	11.18	4.69	1.10	ESE	22.90	21.79	41.92	8.43	
24	34.02	10.98	7.72	2.17	NNE	21.69	23.02	42.12	10.31	
25	33.40	16.20	11.00	3.46	NNE	22.90	24.40	38.40	13.73	
26	34.08	15.14	8.68	2.94	NNW	22.72	24.77	35.83	12.88	
27	34.85	13.88	8.76	1.76	NNE	19.35	23.98	40.30	9.04	
28	35.34	15.14	7.80	1.88	NNE	21.08	24.68	40.50	9.71	
29	34.43	12.36	5.97	1.30	NNE	21.34	24.33	39.78	8.67	
30	35.41	14.25	6.45	1.85	NNE	18.40	25.68	41.17	8.87	
31										
MEAN	28.56	7.14	7.65	1.92		21.29	17.83	45.20	8.75	0.60

TABLE 10.2 - Nomenclature and format for corrected data files.

MON-YR-#.UUR	== HOURLY DATA
MON-YR-#.DAG	== DAILY DATA
MON-YR-#.WND	== DAILY WIND DATA
MON-YR-#.TER	== TOTAL REFERENCE EVAPORATION

FORMAT OF FILES

MON-YR-#.DAG

FIELDS	SIZE	STRING	UNIT
YEAR	I2	(1.2)	
DOY	I3	(3.3)	
TOTAL MISSING DATA	I4	(6.4)	
MEAN RADIATION	F 7.2	(10.7)	W/m^2
TEMP.MAX.	F 6.2	(17.6)	
TEMP.MIN.	F 6.2	(23.6)	
TEMP.AVERAGE	F 6.2	(29.6)	
RADIATION AVERAGE	F 6.2	(35.6)	
WIND AVERAGE	F 6.2	(41.6)	
RAIN	F 5.1	(47.5)	mm
LYSIMETER	F 6.1	(52.6)	mV
LYST STAND.DIVIATION	F 6.1	(58.6)	
CHANGE IN LYSIMETER	F 7.1	(64.7)	mm

MON-YR-#.UUR

FIELDS	SIZE	STRING	UNIT
YEAR	I2	(1,2)	
DOY	I3	(3,3)	
TIME	I2	(6,2)	
RADIATION	F 7.2	(8,7)	W/m^2
TEMPERATURE	F 6.2	(15,6)	
R.H.	F 6.2	(21,6)	%
WIND	F 6.2	(27,6)	m/s
LYSIMETER	F 6.1	(33,6)	mV
RAIN	F 5.1	(39,5)	mm

MON-YR-#.WND

FIELDS		SIZE	STRING	UNIT
YEAR		I2	(1,2)	
DOY		I3	(3,3)	
WIND SPEED		F 6.2	(6,6)	m/s
WIND MAX.		F 6.2	(12,6)	m/s
WIND MIN.		F 6.2	(18,6)	m/s
WIND FREQUENCY	0-45	F 6.3	(24,6)	%/100
WIND FREQUENCY	45-90	F 6.3	(30,6)	%/100
WIND FREQUENCY	90-135	F 6.3	(36,6)	%/100
WIND FREQUENCY	135-180	F 6.3	(42,6)	%/100
WIND FREQUENCY	180-225	F 6.3	(48,6)	%/100
WIND FREQUENCY	225-270	F 6.3	(54,6)	%/100
WIND FREQUENCY	270-315	F 6.3	(60,6)	%/100
WIND FREQUENCY	315-360	F 6.3	(66,6)	%/100
RADIATION TOTAL		F 6.2	(72,6)	MJ/m^2

STATION #1 : DIE BULT

The automatic weather station in the Department of Agrometeorology Observatory (Fig. 10.2) was used primarily to supplement the standard daily meteorological measurements. It has been used extensively by the Agronomy and Agricultural Engineering Departments, and the Institute for Ground Water Studies to calibrate their automatic weather stations. It was also used as an alternate site when the WEST CAMPUS station failed.

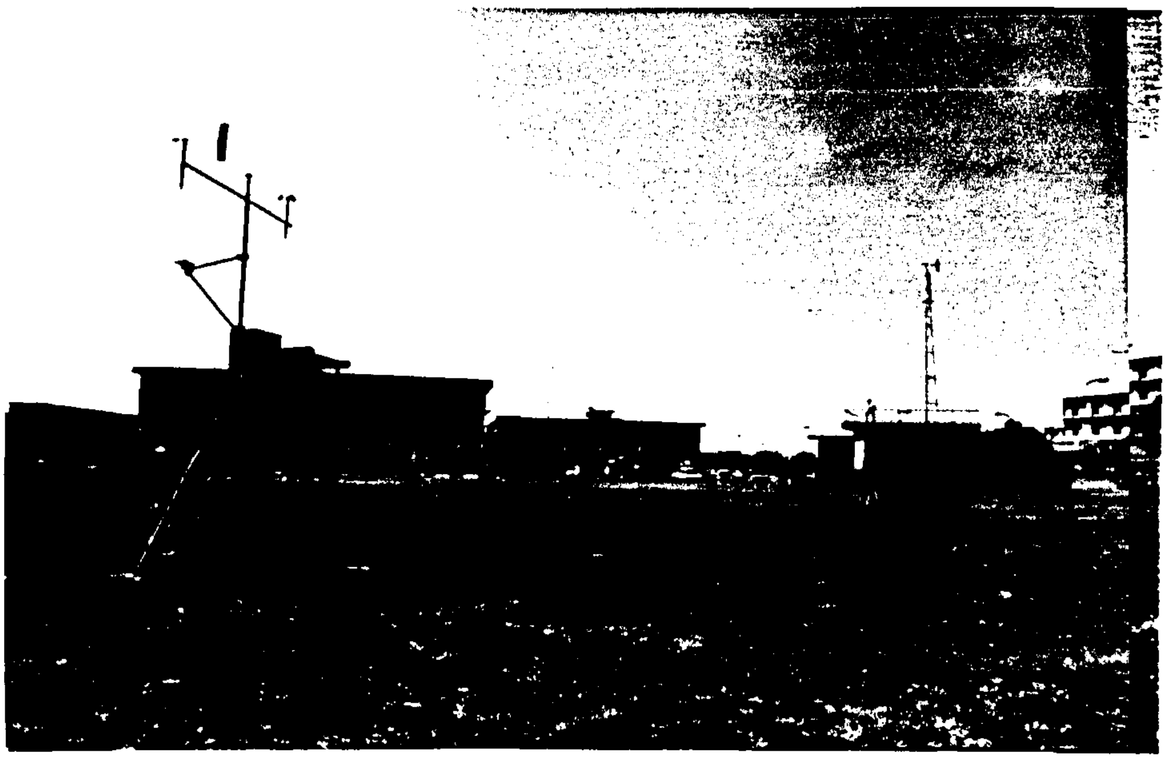


FIG 10.2. Photograph of the automatic weather station located in the UOFS Observatory.

The automatic weather station comprised the basic unit already described plus a second temperature probe used to monitor soil temperature at a depth of approximately 30 cm. The other temperature and humidity sensors were located in a standard Stevenson Screen which also housed other standard meteorological instruments. The two remaining channels on the CR21 were not used.

The calibration for the pyranometer is shown in Table 10.3. The rain gauge and temperature sensors were compared against standards when the station was installed. The anemometer was checked against the Prüfchien anemometer. The humidity sensor was calibrated against a standard aspirated Assman Physchrometer (Table 10.3).

The user-specified input (*4) and output (*1,2,3) programme tables for station #1 are given in Table 10.4 and require 26 intermediate storage locations. Output Table*1 provides hourly mean values of total radiation (kW/m^2) temperatures (^{o}C), relative humidity (%) and the wind speed and vector (m/s, m/s, deg, std.dev.of direction). This programme also logs the time and amount of rainfall (mm). Output Tables*2 & *3 provide station identification, battery voltage and daily total rainfall as well as the daily mean values of the other sensors. Table*2 also provides the maximum and minimum temperatures and their time of occurrence, while Table*3 provides the maximum wind speed, when it occurred, as well as the relative frequency distribution of the wind direction for eight points of the compass (see Table 10.1).

The data from the CR21, as generated by the user-specified tables (*1,2,3) are stored in files MTH-YR.OBS in the following format:-

```
01+TABLE#  02+####  03+####  04+####  05+#### etc.
```

where the individual values in the second and subsequent fields of each record are dependent upon the different programme tables. For this station the records were generated as follows:

```
01+0001  02+DATE  03+TIME  04+RADIATION
                           05+TEMPERATURE
                           06+RELATIVE HUMIDITY
                           07+SOIL TEMPERATURE
                           08+WIND SPEED
                           09+WIND VECTOR
                           10+WIND DIRECTION
                           11+STANDARD DEVIATION OF WIND DIRECTION

01+0002  02+STATION ID     03+BATTERY VOLTAGE
                           04+MAXIMUM TEMP     05+TIME OF MAXIMUM
                           06+MINIMUM TEMP     07+TIME OF MINIMUM
                           08+RAINFALL
                           09+RADIATION
                           10+MEAN TEMPERATURE
                           11+MEAN RELATIVE HUMIDITY

01+0003  02+MAXIMUM WIND SPEED      03+TIME OF MAXIMUM
         04+MEAN WIND SPEED
         05+RELATIVE FREQUENCY OF WIND DIRECTION IN THE NNE
         06   -------------------"---------------------- ENE
         07   -------------------"---------------------- ESE
         08   -------------------"---------------------- SSE
         09   -------------------"---------------------- SSW
         10   -------------------"---------------------- WSW
         11   -------------------"---------------------- WNW
         12   -------------------"---------------------- NNW

01+0249  02+RAIN  03+TIME OF RAIN
```

TABLE 10.3 - The calibration details for the different sensors.

STATION #	SENSOR	DATE	CORRELATION COEFFICIENT	SLOPE	OFFSET	CALIBRATION INSTRUMENT
0001	PYRANOMETER (PY5753)	27-02-84	------	0,1901	0	MANUFACTURER CERTIFICATE
0001	HYGROMETRIX # 8502	17-09-84 17-09-84	0,991 0,985	1,146 1,141	-24,99 -19,68	*ASSMAN *WET-DRY BULB
0002	PYRANOMETER (PY5059)	24-05-83	-----	0,100	0	MANUFACTURER CERTIFICATE
0002	HYGROMETRIX # 8503	20-01-84 12-10-85 18-07-86	0,981 0,988	0,912 0,989	-10,64 -16,94	ASSMAN WET-DRY BULB WET-DRY BULB
0002	LYSIMETER	15-05-84 13-09-85 13-09-85	----- ----- -----	0,322 0,153 0,152	0 0 0	WEIGHBRIDGE WEIGHBRIDGE WEIGHBRIDGE
0002	MET-ONE ANEMOMETER	18-07-86				PRUFCHIEN
0003	PYRANOMETER (PY5060)			0,100	0	MANUFACTURER CERTIFICATE
0003	HYGROMETRIX # 11086	16-10-84 16-10-84	0,994 0,982	1,072 1,149	-17,79 -10,69	*ASSMAN *WET-DRY BULB

* calibration by Miss Weideman - aspirated Assman
unaspirated wet & dry bulb

TABLE 10.4 - The input and output programme tables for DIE BULT.

CR21 Input Table Coding Form

CR21 ID #0001 Start Date Day 40, 1984 Start Time 15:00 SAST

NOTE: Select input program numbers from appendix A of the CR21 Operator's Manual. Specify a multiplier (a) and offset (b) for each sensor using the equation EU = aX + b to convert the sensor output (X) to engineering units. EU = Final Output Engineering Units. IU = Input Units e.g. volts (V), millivolts (MV), and counts.

Sensor Number	Range (EU)	Input Program	Program No.	Multiplier (EU/IU)	Offset (EU)
	Sensor Description and Calibration				Final Output (EU)
1	(V, MV, DC Resistance) SILICON PYRANOMETER mv/kw/m²				kW m⁻²
		Millivolts	11: 2	12: 0.1901	13: 0
2	(V, MV, DC Resistance) POTENTIOMETER WIND VANE				degrees
		Volts/excitation	21: 3	22: 360	23: 0
3	(V, MV, DC Resistance) TEMPERATURE - 30cm SOIL DEPTH				C
		temperature	31: 7	32: 1	33: 0
4	(V, MV, DC Resistance) TEMPERATURE - Stevenson Screen				°C
		temperature	41: 7	42: 1	43: 0
5	(V, MV, DC & AC Resistance) RELATIVE HUMIDITY SENSOR # 9502				%
		Millivolts/excitation	51: 4	52: 6.555	53: -41.44
6	(V, MV, DC & AC Resistance)				Volts
			61:	62:	63:
7	(V, MV, DC & AC Resistance)				
			71:	72:	73:
8	(Pulse counter (4095 counts per scan maximum)) Wind Speed -- contact anemometer		MPH = (1.789)(counts/sec)+1 MPH = (0.0298)(counts/min)+1		m/s
	1-45 m/s	Pulse Counts	81: 6	82: 0.08	83: 0.4470
9	(Pulse counter (15 counts per scan maximum)) Tipping Bucket Raingage		1 tip/m = 1 tip/0.03937 in		Hundreths of an inch
	Variable	Pulse Counts	91: 6	92: 0.20	93: 0

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CR21 Output Table Coding Form

CR21 ID # 0001 Start Date ______ Start Time ______

NOTE: Select output program numbers and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table.

Output Table Number (1, 2 or 3) 1 Output Time Interval (minutes) 03: 60

Table Entry Number	Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Parameter 2
	Output Program and Data Description				Output ID No.
1	SOLAR RADIATION				kW m⁻²
	channel #	N/A	11: 51	12: 1	13: 0
2	TEMPERATURE - Stevenson Screen				°C
	channel #	N/A	21: 51	22: 4	23: 0
3	RELATIVE HUMIDITY - Screen				%
	channel #	N/A	31: 51	32: 5	33: 0
4	SOIL TEMPERATURE - 30cm				°C
	channel #	N/A	41: 51	42: 3	43: 0
5	WIND VECTOR (speed, vector, direction, $\sigma_{direction}$)				
	speed channel	direction channel	51: 56	52: 8	53: 2
6					
			61:	62:	63:
7					
			71:	72:	73:
8					
			81:	82:	83:
9	RAINFALL				mm/hour
	channel #	time interval	91: 57	92: 9	93: 60

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CR21 Output Table Coding Form

CR21 ID # 0001 Start Date ____ Start Time ____

NOTE: Select output program number and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table.

Output Table Number (1, 2 or 3) 2 Output Time Interval (minutes) 03: 1440

Table Entry Number	Output Program and Data Description: Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Output ID No. / Parameter 2
1	STATION IDENTIFICATION				#
	constant	N/A	11: 62	12: 0001	13: 0
2	BATTERY VOLTAGE – Sample				
	channel #	N/A	21: 50	22: 0	23: 0
3	TEMPERATURE – Screen MAXIMUM/TIME				°C/TIME
	channel #	TIME	31: 53	32: 4	33: 1
4	TEMPERATURE – Screen MINIMUM/TIME				°C/TIME
	channel #	Time	41: 54	42: 4	43: 1
5	RAINFALL – TOTAL				MM
	channel #	N/A	51: 52	52: 9	53: 0
6	TOTAL RADIATION – MEAN				kW m⁻²
	channel #	N/A	61: 51	62: 1	63: 0
7	TEMPERATURE – Screen MEAN				°C
	channel #	N/A	71: 51	72: 4	73: 0
8	RELATIVE HUMIDITY – Screen MEAN				%
	channel #	N/A	81: 51	82: 5	83: 0
9					
			91:	92:	93:

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CR21 Output Table Coding Form

CR21 ID # 0001 Start Date ____ Start Time ____

NOTE: Select output program number and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table.

Output Table Number (1, 2 or 3) 3 Output Time Interval (minutes) 03: 1440

Table Entry Number	Output Program and Data Description: Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Output ID No. / Parameter 2
1	WIND SPEED – MAXIMUM/TIME				m s⁻¹/TIME
	channel #	Time	11: 53	12: 8	13: 1
2	WIND SPEED – MEAN				m s⁻¹
	channel #	N/A	21: 51	22: 8	23: 0
3	WIND ROSE				
	channel #	# Sectors (45°)	31: 55	32: 2	33: 8
4	continued......				
	Lower range degrees	upper range degrees	41: 0	42: 0	43: 360
5					
			51:	52:	53:
6					
			61:	62:	63:
7					
			71:	72:	73:
8					
			81:	82:	83:
9					
			91:	92:	93:

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STATION #2 : WEST CAMPUS

The automatic weather station on the WEST CAMPUS (Fig.10.1) was installed over a short grass cover for the continuous monitoring of the appropriate hourly and daily meteorological data at the experimental plot (Fig.10.3). The station was comprised of the basic unit already mentioned. It was also connected to the lysimeter situated some 80m to the north (Fig.10.3). The CR21 monitored the amplified signal from the load cell incorporated in the mechanical weighbridge of the lysimeter. The resistive voltage divider and translator circuit used are shown in Fig. 10.4.

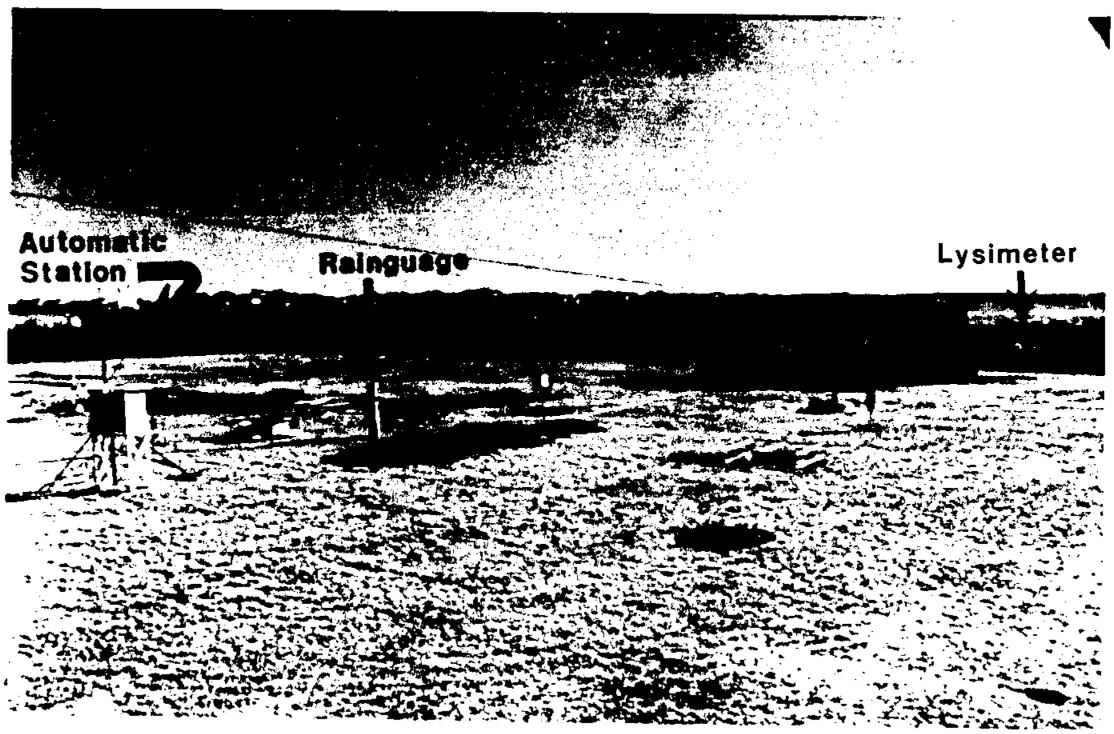

FIG. 10.3. - The experimental plot showing the location of the automatic weather station, lysimeter and other instruments.

The two remaining channels on the CR21 were initially used to evaluate soil moisture probes. They have subsequently been used to compare other sensors against the automatic weather station sensors.

The calibration for the pyranometer is shown in Table 10.3. The raingauge and temperatures were checked against standards when the system was initially installed (November 1983). The Hygrometrix Xnam RH sensor (#8503) was installed in February 1984. Prior to this a wet bulb temperature was used to estimate relative humidity. The Hygrometrix sensor was initially checked against the unaspirated wet and dry bulb temperatures between January 20 and 25,1984 (Table 10.3). Subsequent calibrations are shown in Table 10.3.

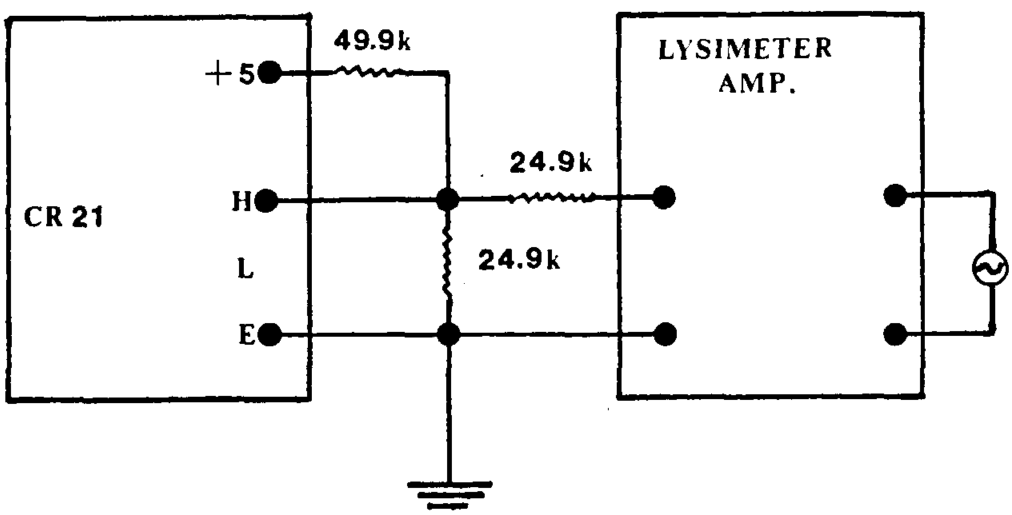

FIG. 10.4. - The resistive voltage divider and translator circuit coupling the lysimeter to the CR21.

The lysimeter was connected to the CR21 on January 27,1984 and calibrated soon after (Table 10.3). On September 9,1985 the load cell on the lysimeter was replaced with a more sensitive one and re-calibrated for the CR21. The CR21 monitored the voltage drop between the positive terminal and earth, while the voltage drop between the negative terminal and earth was monitored manually on a Keithly digital multimeter at selected times.

The BASIC programme for printing the hourly and daily means (Appendix VII) also provided a table of mean hourly values for each month together with their standard deviations (Table 10.5). These will eventually be incorporated in the programme so as to provide standard checks on the raw data.

The input (*4) and output(*1,2,3) programme tables for this station (Table 10.6) require 23 intermediate storage locations. The data format generated by these tables and saved on disc in files MTH-YR.EXP are as follows:

```
01+0001  02+DATE  03+TIME  04+RADIATION
                           05+TEMPERATURE
                           06+LYSIMETER
                           07+RELATIVE HUMIDITY
                           10+WIND SPEED
                           11+LYSIMETER-CONSTANT

01+0002  02+STATION ID     03+BATTERY VOLTAGE
                           04+RAINFALL
                           05+LYSIMETER
                           06+STANDARD DEVIATION IN LYSIMETER

01+0003  02+RADIATION
         03+MEAN WIND SPEED
         04+RELATIVE FREQUENCY OF WIND DIRECTION IN THE NNE
         05  ------------------"--------------------- ENE
         06  ------------------"--------------------- ESE
         07  ------------------"--------------------- SSE
         08  ------------------"--------------------- SSW
         09  ------------------"--------------------- WSW
         10  ------------------"--------------------- WNW
         11  ------------------"--------------------- NNW

01+0249  02+RAIN  03+TIME OF RAIN
```

TABLE 10.5 - An example of mean hourly values for WEST CAMPUS.

d:mar-86.exp

MEAN HOURLY VALUES

Time	Rad	Temp	Rel Hum	Wind speed	Lys
1.00	0.23	18.68	59.38	2.64	1721.00
2.00	0.22	17.90	61.77	2.76	1721.00
3.00	0.26	17.11	66.77	3.41	1721.00
4.00	0.24	16.41	72.99	3.66	1721.00
5.00	0.24	15.78	76.86	2.98	1720.83
6.00	0.45	15.09	79.45	2.94	1720.83
7.00	28.56	14.94	81.65	3.32	1720.83
8.00	141.07	16.48	78.92	4.05	1720.83
9.00	286.00	19.04	72.63	4.48	1721.17
10.00	372.80	21.04	67.20	4.57	1721.83
11.00	454.93	22.96	62.64	4.61	1660.40
12.00	506.33	24.81	57.69	4.38	1667.00
13.00	634.56	26.88	52.24	4.46	1681.80
14.00	576.28	28.16	46.33	4.46	1702.80
15.00	552.33	29.06	43.83	4.21	1711.60
16.00	413.44	29.36	42.61	4.41	1709.80
17.00	262.39	29.26	41.58	4.14	1708.00
18.00	87.77	28.41	41.67	3.77	1706.80
19.00	14.98	26.07	47.89	3.57	1712.60
20.00	0.19	23.31	52.47	3.10	1725.80
21.00	0.21	21.66	54.71	1.91	1735.40
22.00	0.16	20.91	57.97	2.87	1746.80
23.00	0.22	20.17	59.37	2.70	1752.80
24.00	0.22	19.37	61.14	2.81	1753.20

STANDARD DEVIATION

1.00	0.10	3.24	21.28	2.31	196.23
2.00	0.11	2.74	19.86	1.60	196.23
3.00	0.08	2.49	17.62	1.15	195.47
4.00	0.10	2.04	15.32	1.55	195.71
5.00	0.08	2.10	14.75	1.25	195.63
6.00	0.11	2.19	13.68	1.15	195.63
7.00	15.83	1.92	14.34	1.47	195.63
8.00	69.77	1.48	13.60	1.45	195.36
9.00	128.65	2.36	13.76	1.68	194.98
10.00	161.12	3.55	17.38	1.16	195.33
11.00	182.90	4.55	21.76	0.75	141.15
12.00	180.71	4.97	22.68	1.17	133.30
13.00	52.44	4.28	20.32	1.57	126.03
14.00	83.07	3.63	14.49	1.05	134.12
15.00	48.36	3.40	12.49	0.77	143.99
16.00	44.63	2.98	11.89	0.30	142.29
17.00	38.84	2.84	11.50	0.39	140.95
18.00	38.67	2.81	11.62	1.08	139.80
19.00	10.78	4.97	23.53	1.17	144.39
20.00	0.07	4.74	27.52	1.25	159.46
21.00	0.10	4.34	26.97	0.65	172.78
22.00	0.14	4.23	24.85	1.07	190.80
23.00	0.13	4.07	23.95	1.12	199.67
24.00	0.11	3.88	22.76	1.85	200.89

TABLE 10.6 - The input and output programme tables for WEST CAMPUS

CR21 Input Table Coding Form

CR21 ID # 0002 Start Date NOVEMBER 1983 Start Time

NOTE: Select input program numbers from appendix A of the CR21 Operator's Manual. Specify a multiplier (a) and offset (b) for each sensor using the equation EU = aX + b to convert the sensor output (X) to engineering units. EU = Final Output Engineering Units. IU = Input Units e.g. volts (V), millivolts (MV), and counts.

Sensor Number	Sensor Description and Calibration				Final Output (EU)
	Range (EU)	Input Program	Program No.	Multiplier (EU/IU)	Offset (EU)
	(V, MV, DC Resistance)				
1	SILICON PYRANOMETER				kW m⁻²
		millivolts	11: 2	12: 0·10	13: 0
	(V, MV, DC Resistance)				
2	POTENTIOMETER WIND VANE				degrees
		Volts with excitation	21: 3	22: 360	23: 0
	(V, MV, DC Resistance)				
3	LYSIMETER				mV.
		Volts (external source)	31: 1	32: 1000	33: 0
	(V, MV, DC Resistance)				
4	TEMPERATURE Stevenson Screen				°C
		temperature	41: 7	42: 1	43: 0
	(V, MV, DC & AC Resistance)				
5	RELATIVE HUMIDITY % SENSOR # 8503				%
		millivolts/excitation	51: 4	52: 6.062	53: -29.29
	(V, MV, DC & AC Resistance)				
6					Volts
			61:	62:	63:
	(V, MV, DC & AC Resistance)				
7					
			71:	72:	73:
	Pulse counter (4095 counts per scan maximum)				
8	Wind Speed — contact anemometer		MPH = (1.789)(counts/sec)+1 MPH = (0.0298)(counts/min)+1		m/s
	1-45 m/s	Pulse Counts	81: 6	82: 0.08	83: 0.4470
	Pulse counter (15 counts per scan maximum)				
9	Tipping Bucket Raingage		1 tip/m = 1 tip/0.03937 in		Hundreths of an inch
	Variable	Pulse Counts	91: 6	92: 0.20	93: 0

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CR21 Output Table Coding Form

CR21 ID #0002 Start Date Start Time

NOTE: Select output program number and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table.

Output Table Number (1, 2 or 3) 1 Output Time Interval (minutes) 03: 60

Table Entry Number	Output Program and Data Description				Output ID No
	Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Parameter 2
1	TOTAL RADIATION per HOUR				
	channel #	N/A	11: 52	12: 1	13: 0
2	TEMPERATURE – Screen MEAN				°C
	channel #	N/A	21: 51	22: 4	23: 0
3	LYSIMETER – MEAN				mV
	channel #	N/A	31: 51	32: 3	33: 0
4	RELATIVE HUMIDITY – MEAN (Screen)				%
	channel #	N/A	41: 51	42: 5	43: 0
5					
			51:	52:	53:
6					
			61:	62:	63:
7	WIND SPEED – MEAN				ms⁻¹
	channel #	N/A	71: 51	72: 8	73: 0
8	LYSIMETER – (MEAN – 500mV)				mV
	channel #	1000 + constant	81: 66	82: 3	83: 1500
9	RAINFALL – per HOUR				mm/hr
	channel #	TIME	91: 57	92: 9	93: 60

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CR21 Output Table Coding Form

CR21 ID # 0002 Start Date ______ Start Time ______

NOTE: Select output program number and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table

Output Table Number (1, 2 or 3) 2 Output Time Interval (minutes) 03: 1440

Table Entry Number	Output Program and Data Description				Output ID No.
	Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Parameter 2
1	STATION IDENTIFICATION				#
	constant	N/A	11: 62	12: 0002	13: 0
2	BATTERY VOLTAGE – Sample				V
	channel #	N/A	21: 50	22: 0	23: 0
3	RAINFALL TOTAL/day				mm/day
	channel #	N/A	31: 52	32: 9	33: 0
4	LYSIMETER – MEAN				mV
	channel #	N/A	41: 51	42: 3	43: 0
5	LYSIMETER – STANDARD DEVIATION				
	channel #	N/A	51: 61	52: 3	53: 0
6					
			61:	62:	63
7					
			71:	72:	73:
8					
			81:	82:	83:
9					
			91:	92:	93:

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CR21 Output Table Coding Form

CR21 ID # 0002 Start Date ______ Start Time ______

NOTE: Select output program number and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table

Output Table Number (1, 2 or 3) 3 Output Time Interval (minutes) 03: 1440

Table Entry Number	Output Program and Data Description				Output ID No.
	Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Parameter 2
1	TOTAL RADIATION – MEAN				$kW\ m^{-2}$
	channel #	N/A	11: 51	12: 1	13 0
2	WIND ROSE – direction				#/45°
	channel #	# divisions	21: 55	22: 2	23 8
3	continued				
	low range	high range	31: 0	32: 0	33 360
4					
			41:	42:	43
5					
			51:	52:	53
6					
			61:	62:	63
7					
			71:	72:	73
8					
			81:	82:	83
9					
			91:	92:	93

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STATION #3 : VAALHARTS (JUNE-DECEMBER,1984 and 1985)

This automatic weather station was deployed at the Vaalharts Wine Cooperative Meteorological Site during the wheat season of 1984. The station was comprised of the basic unit. However the Stevenson screen was replaced by a radiation shield mounted to the main upright of the tripod. All the remaining channels were left vacant. The user-specific programmes for the CR21 were the same as those of Station #1 (Table 10.4). The automatic weather station data was retrieved on cassette tapes once a week from Vaalharts.

In June, 1985 the automatic weather station was moved to the farm of Japie Smit at Hartswater to enable direct telecommunication linkage between the CR21 and the Department of agrometeorology Sperry PC at the UOFS. The CR21 was interfaced (SC232 interface unit) to an asynchronous dial-up ITT Data Modem (Model 1161) supplied by the General Post Office. The SC232 was powered by 16VAC supply (Fig. 10.5) drawn from the 12 VDC battery of the station. The 12VDC lead-acid battery was continuously charged by a 220VAC trickle charger. The 220VAC mains required for the trickle charger and modem were supplied by Mr Smit, as was the telephone line.

Before the third station was installed at Vaalharts/Hartswater it was erected alongside Station #1 and the sensors compared (Table 10.7. All the sensors were highly correlated (r>0.99). The pyranometer, hygrometrix and met-one sensors also had regression

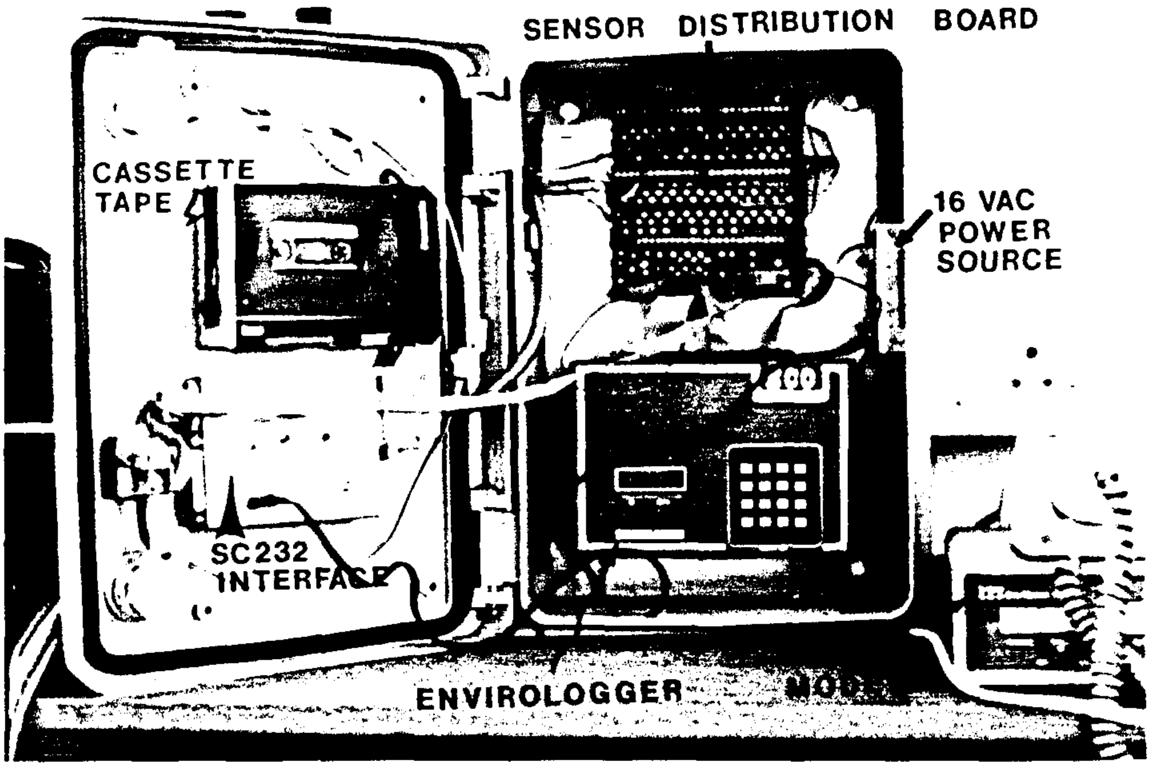

FIG. 10.5 - Photograph of the components of the telecommunication system.

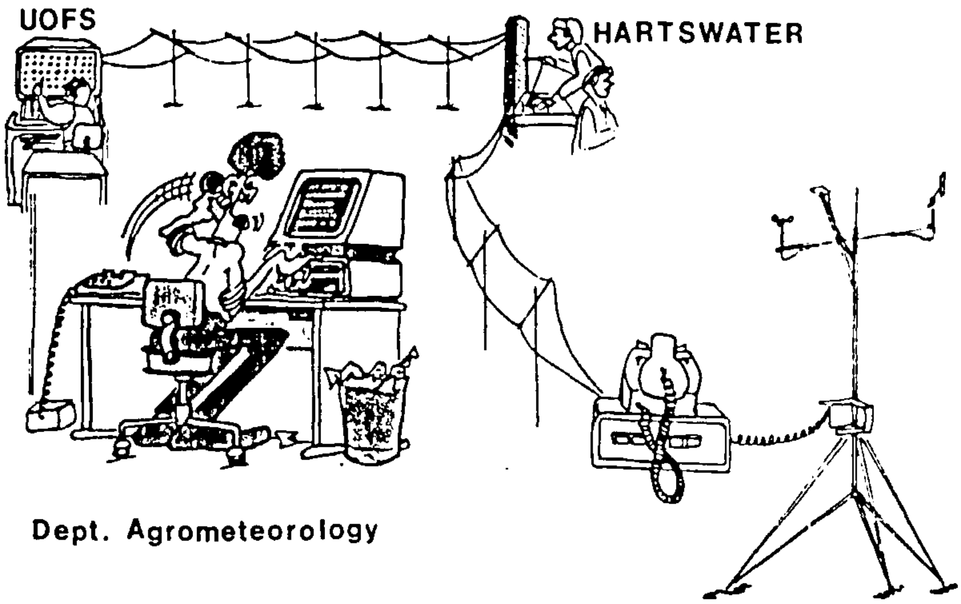

FIG. 10.6 - Schematic diagram of the telecommunication system linking the automatic weather station with UOFS.

TABLE 10.7 - CORRELATIONS AND REGRESSION ANALYSIS OF STATION #1 AND STATION #3 AT THE OBSERVATORY (DIE BUILT)

SENSOR	CORRELATION	SLOPE	INTERCEPT
RADIATION	1,00	0,92	-0,004
TEMPERATURE	0,99	1,21	-3,76
REL. HUMIDITY	1,00	1,07	14,18
WIND SPEED	0,99	1,01	-0,04

coefficients (slope) that were within 8% of unity. The intercept for the humidity sensor however showed a consistent difference of >14%. This difference and that exhibited by the temperature sensors could be caused by the use of a radiation shield for Station #3 instead of a Stevenson screen.

The hardware for this station is shown in the schematic diagram in Fig. 10.6. The procedure for accessing the CR21 required the cooperation of two manually operated switch boards at the UOFS and Vaalharts Post Office. Initially this caused some minor problems which were quickly rectified. Direct access to the station via the telecommunication linkage was scheduled for three specific times each week (Monday, Wednesday and Friday). Mr Smit arranged to switch the telephone modem to the CR21 for an hour on each occasion. During which time the data stored on the internal memory was dumped to the Sperry PC at the UOFS. Problems were encountered with the system which are believed to be due to excessive noise on the telephone line during extremely windy conditions. Since the UOFS switch board closed at regular times and over weekends it was not always possible to retrieve some data before the memory locations were updated with the latest information. The cassette tape, however, operated simultaneously and independently of the telecommunications and consequently the data lost via telecommunication linkage could be obtained by physically retrieving the cassette from Hartswater.

Internal storage requirements had to be minimized. The maximum available storage on the CR21 is 608 words. In order to ensure at least 36 hours between data retrievals (Friday to Monday), the user-specified output Table *1 had to be altered. Only the information essential for numerical simulation modelling (Table. 10.9) was stored. Table *2 and *3 were not used. In this way only 4 intermediate storage locations were required.

Once communication with the CR21 had been established, the CR21 would respond to the commands listed in Table 10.8. Thus the individual sensors or any portion of the internal memory could be monitored at any time. All responses from the CR21 were displayed on the Sperry PC video and subsequently saved in specified files.

The data was received and saved in files with the following format:

```
01+0001  02+DATE  03+TIME  04+RADIATION
                           05+TEMPERATURE
                           06+RELATIVE HUMIDITY
                           07 WIND SPEED

01+0249  02+RAIN  03+TIME OF RAINFALL
```

TABLE 10.8. THE COMMANDS AND RESPONSES FOR TELECOMMUNICATION WITH THE CR21

VALID COMMANDS	RESPONSE FROM CR21
A	ADVANCE AND DUMP NEXT MEMORY LOCATION
B	BACKUP TO PREVIOUS MEMORY LOCATION
C (DOY & TIME)	D:#### T:####
(BATTERY VOLTAGE)	00:####
(READING SENSOR #1	01:####
#2	02:####
etc	
#n	On:####
HHMMG where HH=HOUR MM=MINUTES	RESET CLOCK
@ (CURRENT MEMORY LOCATION)	??:####
D (DUMP MEMORY FROM CURRENT MEMORY LOCATION TO THE MOST RECENT STORAGE)	01:000n 02:DOY 03:TIME 04:DATA etc
E (END TRANSMISSION)	CLOSES TRANSMISSION
### (POSITION MEMORY LOCATION)	

TABLE 10.9 - The input and output tables for HARTSWATER STATION.

CR21 Input Table Coding Form

CR21 ID #0003 Start Date ______ Start Time ______

NOTE: Select input program numbers from appendix A of the CR21 Operator's Manual. Specify a multiplier (a) and offset (b) for each sensor using the equation EU = aX + b to convert the sensor output (X) to engineering units. EU = Final Output Engineering Units. IU = Input Units e.g. volts (V), millivolts (MV), and counts.

Sensor Number	Sensor Description and Calibration / Range (EU)	Input Program	Program No.	Multiplier (EU/IU)	Offset (EU)	Final Output (EU)
1	(V, MV, DC Resistance) SILICON PYRANOMETER	millivolts	11: 2	12: 0.	13: 0	kW m⁻²
2	(V, MV, DC Resistance) POTENTIOMETER WIND VANE	volts/excitation	21: 3	22: 360	23: 0	degrees
3	(V, MV, DC Resistance)		31:	32:	33:	
4	(V, MV, DC Resistance) TEMPERATURE - Radiation Shield	temperature	41: 7	42: 1	43: 0	°C
5	(V, MV, DC & AC Resistance) RELATIVE HUMIDITY - Rad Shield (SENSOR 11086)	millivolts/excitation	51: 4	52: 7.01	53: -60.54	%
6	(V, MV, DC & AC Resistance)		61:	62:	63:	Volts
7	(V, MV, DC & AC Resistance)		71:	72:	73:	
8	Pulse counter (4095 counts per scan maximum) Wind Speed -- contact anemometer; MPH = (1.789)(counts/sec)+1; MPH = (0.0298)(counts/min)+1; 1-45 m/s	Pulse Counts	81: 6	82: 0.08	83: 0.4470	m/s
9	Pulse counter (15 counts per scan maximum) Tipping Bucket Raingage; 1 tip/m = 1 tip/0.03937 in; Variable	Pulse Counts	91: 6	92: 0.20	93: 0	Hundreths of an inch

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CR21 Output Table Coding Form

CR21 ID ≠ 0003 Start Date ______ Start Time ______

NOTE: Select output program number and parameters from appendix B of the CR21 Operator's Manual. Output ID numbers 1, 2 and 3 identify table number, day and time. ID numbers 4 and greater identify data generated by output programs. Only positive integers are used to program the output table.

Output Table Number (1, 2 or 3) 1 Output Time Interval (minutes) 03: 60

Table Entry Number	Output Program and Data Description / Param 1 descrip.	Param 2 descrip.	Program No.	Parameter 1	Parameter 2	Output ID No
1	RADIATION - MEAN; channel #	N/A	11: 51	12: 1	13: 0	kW m⁻²
2	TEMPERATURE - Radiation Shield; channel #	N/A	21: 51	22: 4	23: 0	°C
3	RELATIVE HUMIDITY - Radiation Shield; channel #	N/A	31: 51	32: 5	33: 0	%
4	WIND SPEED; channel #	N/A	41: 51	42: 8	43: 0	m s⁻¹
5			51:	52:	53:	
6			61:	62:	63:	
7			71:	72:	73:	
8			81:	82:	83:	
9	RAINFALL TOTAL; channel #	TIME	91: 57	92: 9	93: 60	mm/hr

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SUMMARY AND CONCLUSIONS

The WEST CAMPUS station has been operational for more than 24000 hours during which time approximately 1300 hours down-time occurred. This 5% loss in data was due almost entirely to power failures which went undetected for several days in most cases, but exceeded 22 days in January 1985 (~50% of the total downtime). A similar down-time for DIE BULT was also due to power failure. However, in the case of the third station, the power problem was rectified and the low data loss was due entirely to excessive noise on the telecommunication lines.

Once the automatic weather station had been calibrated against standards, they were readily deployed in the field. The department of Agronomy, Agricultural Engineering and the Institute of Ground Water Studies compared their Automatic weather stations with DIE BULT Station before deploying them in the field. In some cases this was accomplished by undergraduate students with little difficulty. The major problem appeared to be installing the user specified programme Tables. The design of these programme tables requires a thorough understanding of the CR21 capabilities and available software. The CR21 has 22 different output programmes, intermediate storage and parameter passing capabilities which would be difficult to use without suitable training. However, once designed they can be installed with little difficulty by undergraduates.

The ASCII data from the automatic weather station is in a simple, readable form that can be easily interpreted from printouts (Table 10.10). It is readily accessed using string form in BASIC programmes. The BASIC programmes developed for disseminating the automatic weather station data are modular in form and can easily be modified to suit other users. They have been used by the Institutes of Ground Water Studies and Environmental Studies for the analysis and presentation of experimental data.

TABLE 10.10 - The data format for the automatic weather station.

TABLE #1	DOY	TIME	(RADIATION)	(TEMPERATURE)	(HUMIDITY)
01:0001	02:0xxx	03:xx00	04:0.xxx	05:xx.xx	06:xx.xx etc.
01:0001	02:0xxx	03:xx00	04:0.xxx	05:xx.xx	06:xx.xx etc.
01:0001	02:0xxx	03:xx00	04:0.xxx	05:xx.xx	06:xx.xx etc.

CHAPTER 11

COMPUTATION AND DISSEMINATION OF INFORMATION

A wealth of experience in the operation of irrigation scheduling service using weather data was obtained during the period 1982 to 1985. This chapter serves as a short summary describing the *modus operandi* such service should adopt.

Objective of weather service for scheduling irrigation

The objectives of such a service are:

(i) keep accurate account of water use and soil water budget on individual irrigation plots on diverse farms,

(ii) provide weekly advisories to managers which indicate the day on which the next irrigation should be applied.

(iii) regular monitoring of the performance of managers of enterprises.

(iv) assist managers in planning strategies and scheduling at the outset of the season.

The prediction accuracy of the onset of crop water stress should be approximately two days.

Description

To curtail computing time a simulation model using daily time steps should be used. An hourly (PUTU 9) and daily (PUTU 9.86) version are available.

Where a large number of farmers are involved, individual plots should be grouped according to soil type and planting date in order to limit computing time. Such arrangement is probably logistically the most sound. The necessary computer software has been developed.

Hourly values of crop total evaporation, Em, should be computed from weather data. The daily values of Em are found by integrating these over the daylight period.

Dissemination of data

Information most valuable to managers is outlined under the above stated objectives. It includes: indication of the danger of onset of water stress; the daily water use over the past seven days; the percolation of water out of the root zone; the expected timing of the next irrigation; monitoring of the current plant available water in the root zone, and an assessment of the managers' performance. The necessary standard forms and figures for disseminating this information have been designed. They can be found in Table 9.4, 9.5, 9.6 and 9.7. Graphical presentations such as Fig. 7.2 and 7.4 etc, Fig. 9.1 and 9.2 offer simple effective ways of communicating information to managers.

Deep percolation losses, illustrating poor irrigation management are illustrated in Fig. 9.2 This is an actual case from the 1985 season. Indeed, Fig 9.2 made the farmer involved fully aware, for the first time, just how serious such mismanagement could prove to be. The knowledge that so much deep percolation had occurred early in the wheat growing season was of immense value to him.

Managers greatly appreciate personal contact. The operators of the weather service should regularly visit clients. Apart from meeting the needs of the manager, this is a source of valuable information to the weather service operator. Such feedback will certainly lead to an improved service.

The summary of performance provided by Table 9.7 also proved to be particularly useful when conveying information to the farm managers.

<u>Strategy in times of restricted water supply</u>

Information most urgently required by farmers involves drought sensitivity to and water requirement of crops during given growth stages throughout the growing season. Hence the necessity for timeous visits to the farm manager.

Decision making regarding the most suitable strategy in times of restricted water supply form an indispensable part of the service. Some form of strategy planning is always required. Useful indications as to how this might be achieved, are provided in Chapter 12 and Table 8.2.

CHAPTER 12

THE INFLUENCE OF WEATHER UPON DECISION MAKING FOR OPTIMAL IRRIGATION SCHEDULING

INTRODUCTION

When water restrictions apply, as was the situation during the period 1983-86, the farmer is faced with the dilemma of finding the most profitable irrigation strategy. His objective must be to maximize whole farm profit with the given water supply, rather than the maximization of mean farm yield (t/ha), or the maximization of water use efficiency (kg/(ha^2 mm)). It is precisely this question with which the farm manager confronts the adviser.

The procedures of profit maximization are well described by Doll and Orazem (1984) and the total dependence of such analysis upon suitable crop-water production functions is illustrated by Ayer and Hoyt (1981).

OBJECTIVE

The aim of this work was to establish a theory for planning irrigation strategies which maximize:

(i) yield, or
(ii) water use efficiency, or
(iii) profits per hectare, or
(iv) whole farm profit.

THEORY

An analysis of the economics of irrigation scheduling requires a crop-water production function. The ensuing argument can best be followed with reference to Fig. 12.1. Simple linear production curves have been reported for wheat by Streutker (1983a), Doorenbos and Kassam (1979) and Hanks and Hill (1980). Similar curves are available for other crops (see Streutker, 1983b). Production functons are not linear however (see Ayer and Hoyt, 1981). Hence the construction of theoretical or experimental crop-water production functions is a pre-requisite to this type of analysis. Here, a simple function for wheat will be derived and applied to illustrate the principles involved. It was found using the PUTU 9.86 wheat crop growth model. Such production functions are dependent upon climate and soil physical and chemical characteristics. They must be constructed for each specific situation and hence a reliable crop growth model greatly simplifies analysis.

The parameters necessary for analysing the influence of weather upon the profits of irrigating winter wheat were defined as follows:

Y is the total physical product (TPP) or output (yield) (t/ha).

X is the variable input - in this case the quantity of water applied (ha mm).

APP is the average physical product

APP = Y/X for the straight line intersecting the origin and the point on the production curve corresponding to the water application under consideration (t/ha^2 mm)) - see Fig. 12.1a

MPP, the marginal physical product, is the change in output resulting from unit change in input (MPP = $\Delta Y/\Delta X$ at any given X on the ccrop-water production curve) (t/ha^2 mm) - see Fig. 12.1a.

Py is price per unit output (R /t).

Px is price per unit variable input ($R/(ha^2$ mm)).

TC is the total cost in Rands (R/ha).

TVC is the total variable cost; TVC = Px.X (R/ha).

TVP is the total value product; TVP = Py.Y (R/ha).

TFC is the total fixed cost per unit area (R/ha).

VMP is the value of the marginal physical product ($R/(ha^2$ mm)).

<u>The simple profit model</u>

Doll and Orazem (1984) express the simple profit equation as:

$$\underline{Profit} = TVP - TC \quad ..(12.1)$$

$$= TVP - TVC - TFC \quad ..(12.2)$$

$$= Py . Y - Px . X - TFC \quad ..(12.3)$$

Where Y = f(X) and is known as the crop-water production function. Thus <u>Profit</u> = Py . f(X) - (Px .X) - TFC

To maximize profit with respect to water application

$$\delta \underline{\text{Profit}}/\delta X = Py.\Delta Y/\Delta X - Px = 0$$

$$= Py.MPP - Px = 0, \qquad \text{by definition.}$$

Hence, for maximum profit, the following must be true

$$MPP = Px/Py \qquad ..(12.4)$$

Px/Py is known as the price ratio line.

The condition for maximum profit expressed by Eqn 12.4 is

$$Py.MPP = Px \text{ or } VMP = Px \qquad ..(12.5)$$

where, VMP is the value of the marginal product, i.e. the Rand value of the yield associated with each succeeding unit of applied water ($R/(ha^2\ mm)$).

The three stages of production

Doll and Orazem (1984) describe three stages of production.

STAGE I - here MPP > APP

As X increases, APP increases throughout STAGE I reaching a maximum at the end of STAGE I. Hence STAGE I ends when

$$\delta APP / \delta X = 0 \text{ and } MPP = APP$$

Doll and Orazem (1984) maintain that, in practice, no successful enterprise operates in this range. It is illogical so to do, because each increase in applied water attains an increased mean yield (APP). Only when STAGE II is reached is the strategy economically sound. Within STAGE I a point is reached where MPP is a maximum. Thereafter MPP decreases. This is known as the region of diminishing returns.

STAGE II - here MPP $\leq$ APP

Here, as X increases, MPP is decreasing. Thus, this stage falls entirely within the region of diminishing returns. In this stage however, MPP is always greater than zero.

STAGE III - here MPP < 0

Production in this stage is irrational because the farmer could attain the same production with a smaller input (water application).

<u>The elasticity of production</u>, ϵ_p, is defined:

$$\epsilon_p = \frac{\text{percent change in output}}{\text{percent change in input}} \qquad \text{(dimensionless)}$$

$$\epsilon_p = \Delta Y/Y \;/\; \Delta X/X = X/Y . \Delta Y \;/\; \Delta X = \Delta Y/\Delta X \;/\; Y/X = MPP \;/\; APP$$

Generally, for economic systems, the possible production interval, is the interval bounded by variable input values corresponding to $0 < \epsilon_p < 1$ (Doll and Orazem, 1984). When MPP = APP then $\epsilon_p = 1$. Theoretically this is the beginning of STAGE II. When MPP > APP then $\epsilon_p > 1$ (STAGE I) a 1% change in input will produce a greater than 1% change in output. When MPP = 0,

$\epsilon_p = 0$, STAGE III is reached. Production beyond this point is uneconomical. Hence irrigation scheduling must be planned always to proceed in STAGE II - which is in the realm of diminishing returns.

Water use or irrigation efficiency, ϵ_w, is defined: $\epsilon_w = Y/X$. (NOTE ϵ_w = APP in this case.) It reaches a maximum when APP is a maximum (see Xm in Fig. 12.1a). As will be seen, this coincides with neither maximum MPP nor maximum profit. Furthermore, it coincides with the end of STAGE I for an irrigation enterprise.

IRRIGATION STRATEGIES

(i) Maximum yield is obtained at the apex (A) of Fig. 12.1a. This corresponds to a water application of Xo mm. In practice water application should never exceed Xo as this is complete wasteage.

(ii) Maximum irrigation water use efficiency per unit land area occurs when APP = MPP i.e. when $\delta APP/\delta X = 0$.

(iii) Maximum profits per ha are attained however when VMP = Px (see Eqn 12.5), i.e. when the value of the marginal physical product equals the price per unit of water applied (see Fig. 12.1c). Only when the price of water is zero will the profit maximizing and yield maximizing level of water coincide. This never occurs.

(iv) Maximum whole farm, or region, profit does not however result by ensuring maximum profits (Case iii) on each hectare of irrigated land. The latter is determined by the amount of water available. Whole farm, <u>or region</u>, profits are maximised by increasing the area irrigated and applying less water than that level which maximizes profit per unit area on condition that APP > MPP.

The solution to this problem (Strategy iv) is site specific and totally dependent upon the shape of the production function. The latter is of course a function of climate, soil character and cultivation practices. The relevant fundamental <u>equimarginal principle</u>, derived by Doll and Orazem (1981) for the case where input (water) is limited, reads:

> Maximum whole farm, or region, profits are attained when the marginal product of the input is the same in each enterprise (irrigated unit).

The solution to the problem thus reduces to numerical computation of the production function.

The pertinent rules are:

1. The amount of water applied to each unit of land irrigated must ensure operation within STAGE II, and

2. Equal amounts of water must be applied to each unit, provided the same type of irrigation system is used on all lots. If not, the criterion.

$\Delta Y2/\Delta Y1 = Py1/Py2$ ... etc. applies where 1, 2...etc refer to different types of system.

The theoretical procedure required to maximise whole farm, or region, profits from irrigation will now be described.

Given a water supply S (m^3), let 'lo' and 'up' denote lower and upper limits. Compute from the production function the limits of STAGE II on a single hectare, thus:

1. Lower limit Xlo = X where APP = MPP or Xm

   Upper limit Xup = X where MPP = Px (maximum profit per unit area).

2. The total number of hectare able to be irrigated, H, will lie between $Hlo = \epsilon s . S/Yup10$ and $Hup = \epsilon s . S/10.Xlo$

   ϵs = efficiency of supply of water to the lands.

   (Note: 1 ha mm = $10m^3$)

3. For irrigated units of size Hu, the most effective number of units N would be all integer numbers between Hlo/Hu and Hup/Hu.

APPLICATION OF THIS THEORY TO IRRIGATION PRACTICE

A simple example will be used to illustrate use of the theory.

Theoretical crop-water production function

A hypothetical crop water production function was created. This was done by selecting several irrigation strategies (see Table 12.0) and running the PUTU 9.86 model with weather input data from the West Campus. No rainfall was assumed. The scheduling ensured that no stress occured during secondary root development and anthesis. A soil layer depth of 0,15 m and the lysimeter soil were selected. The results obtained from this procedure are plotted in Fig. 12.2. From this curve the following results were extracted:

1. the maximum yield (6,6 t/ha) was obtained at a water application of Xo = 620 mm.

2. the maximum water use efficiency of 12,3 kg/(ha mm) area occurred at Xm = 460 mm.

3. values of APP and MPP from which strategy decisions may be made are quoted in Table 12.1. STAGE II, the region of diminishing returns resides between water applications of Xd = 360 mm and Xo = 620 mm, or between eight and 14 irrigations.

4. Whole farm profits may be maximised between 460 < X < 620 mm, i.e. 10 and 14 irrigations. It is asumed that in the case of flood irrigation Px $\doteq$ 0.

5. the number of plots irrigated may be calculated given the size of plot and the water supply available, S.

Significance to West OFS

While the production curve, Fig. 12.2, is theoretical it should be reasonably representative of wheat in the central and western OFS. At Hartswater, evaporation will be higher, but the soil and cultivation practices are typical of the region. As a starting point therefore the results are worthy of scrutiny.

The 1983 strategy reported for Site A in Table 8.2 was an attempt to solve the problem subjectively. Much experience with the matter was obtained, but the recommended irrigation frequency (eight) fell two short of the theoretical minimum requirement. It might therefore have been more profitable to have selected a strategy encompassing a frequency of ten for Hartswater.

The suggested frequency of 10 to 14 agrees well with general practice in Hartswater. Here 11 irrigations are expected to produce 6-7 t/ha of wheat grain (see Table 9.3, 8.4, X.1 and X.8).

The MPP and APP derived from the hypothetical production curve, Fig. 12.2 and described in Table 12.1 could prove useful in preliminary irrigation strategy planning in the western OFS.

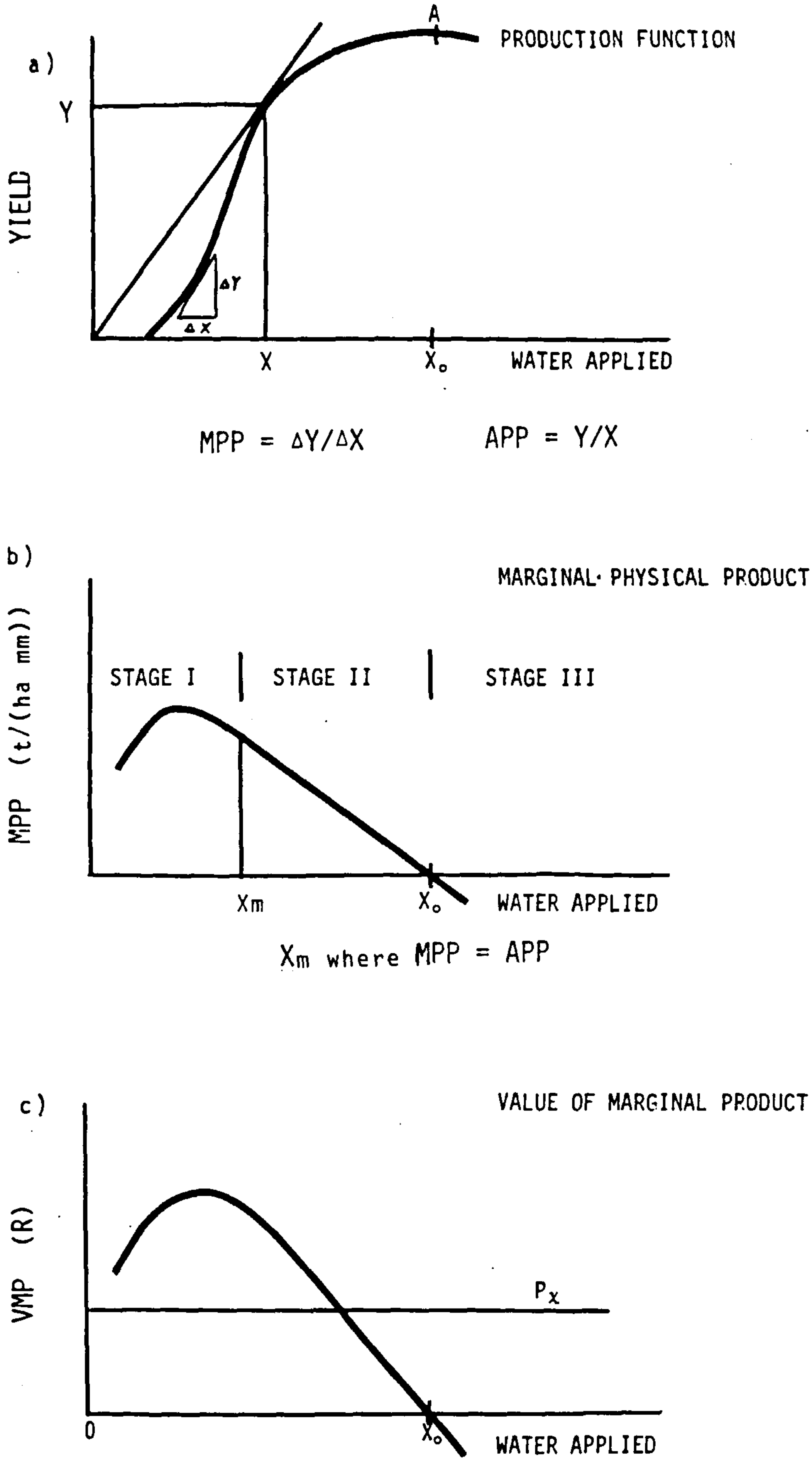

FIG. 12.1 - Figures illustrating how the crop-water production function, Fig. 12.1a, may be used to analyse the various stages of irrigation and to determine Xm, Xo, APP and MPP. (After Ayer and Hoyt, 1981)

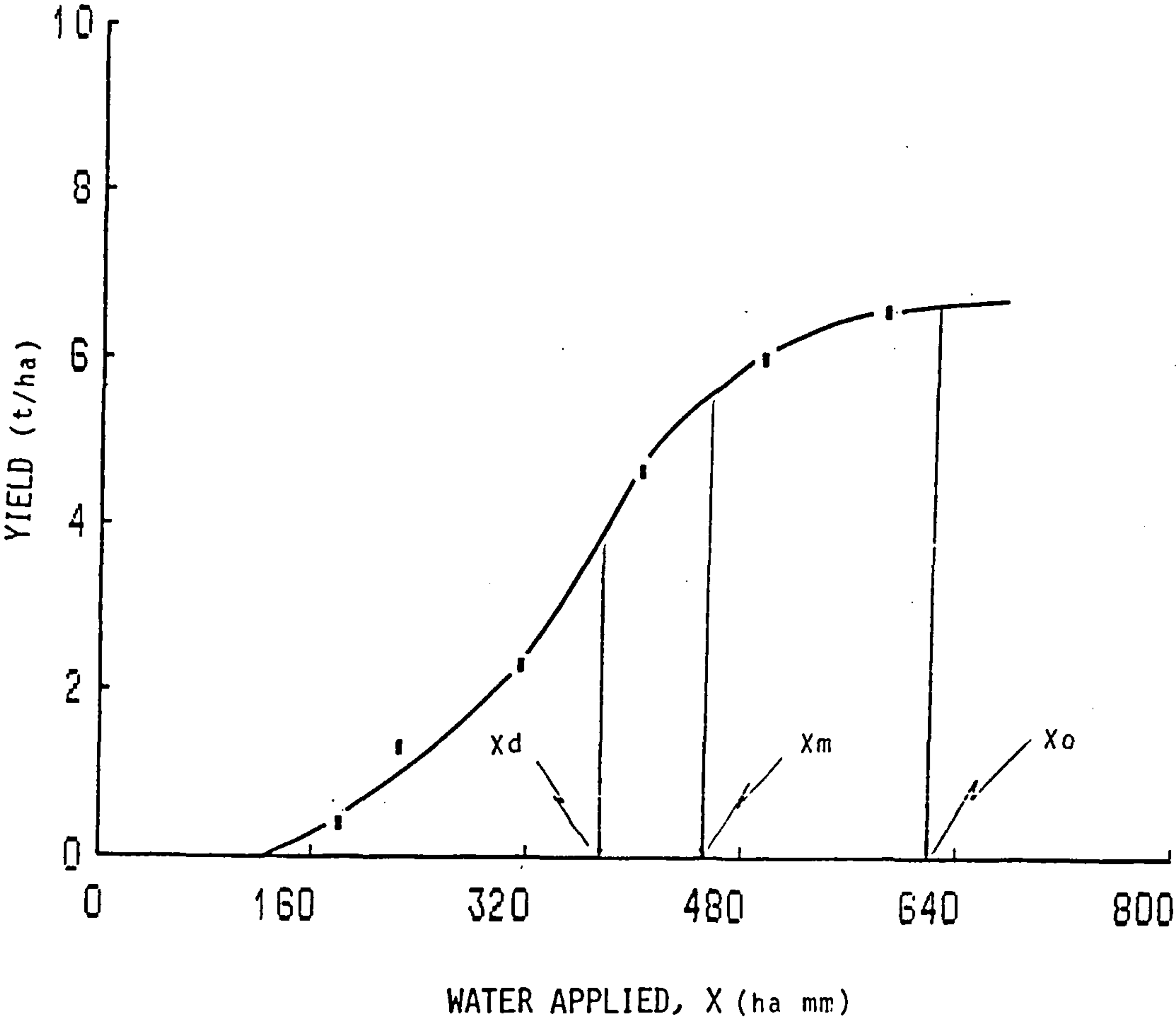

FIG. 12.2 - The crop-water production curve using several hypothetical irrigation strategies together with weather for West Campus in the wheat crop growth model PUTU 9.86. The water application producing the onset of diminishing returns, maximum water use efficiency and the maximum yield are denoted by Xd, Xm and Xo respectively.

TABLE 12.0 - Day of the year (DOY) on which theoretical irrigations, and amounts, were applied in PUTU 9.86 in order to generate the hypothetical crop-water production curve for wheat on West Campus.

DOY	IRRIGATIONS (mm)					
180	45	45	45	45	45	45
200			45	45	45	45
215		45				
220			45	45	45	45
225	45					
240				45	45	45
250		45				
260			45	45	45	45
270				45	45	45
278	45	45	45			
280				45	45	45
290			45	45	45	45
300					45	45
310	45	45	45	45	45	45
320					45	45

TABLE 12.1 - Values of APP and MPP derived from the hypothetical crop water production curve.

IRRIGATION FREQUENCY	WATER	APP	MPP
	(mm)	(kg/(ha mm))	(kg/(ha mm))
7	300	6,5	11,4
	340	8,5	25,0
8	360	9,4	27,8
	380	10,2	25,0
9	420	11,6	21,0
10	460	12,2	12,3
11	500	12,0	9,5
12	540	11,7	6,6
13	580	11,3	2,8
	620	10,5	0,0

CHAPTER 13

SUMMARY

The use of weather data from an automatic weather station for scheduling the irrigation of winter wheat was investigated. The method devised, accommodated individual plots of land as well as numerous farms. The study was carried out with experiments conducted on the experimental site at the Agrometeorological Observatory on the West Campus of the University of the Orange Free State, Bloemfontein and on several farms in the Hartswater district.

An existing crop growth simulation model was refined and tested for the purpose of scheduling irrigation. Major modifications entailed including a multi-layered soil and a water extraction routine using an exponential rooting distribution. The function controlling total evaporation loss from the vegetative surface under incomplete leaf cover was also refined. The model was shown to provide accurate simulations of water use and the onset of crop water stress in the 1985 season on West Campus. Comparisons were conducted in a lysimeter and on certain experimental plots. The lysimeter was installed specially for this purpose. It, together with an irrigation supply system was established during the experimental period.

Micrometeorological measurements were utilized on the experimental site to validate the modified Penman-Monteith equation for estimating crop total evaporation using weather data. A slightly modified version of this model was and is now being utilized to estimate crop total evaporation from data provided by the automatic weather station. Other micrometeorological techniques were tested, but found to be inferior to the Penman-Monteith equation.

An automatic weather station was commissioned in Hartswater to provide weather data for the service. It was shown that data could be telemeterized via the normal telephonic network. The connection was effected via a manually operated exchange at the UOFS and the manual exchange in the district of Hartswater. Hence, the data transmission and acquisition should function satisfactorily under all conditions in any region. The initial technical problems encountered with the initial commissioning of the system were overcome. The necessary computer software was developed for the manipulation and compilation of the data and for the simulation procedures. Furthermore, the modus operandi for disseminating irrigation scheduling prognoses to individual farm managers was standardised. A good understanding was created with certain farmers in the Hartswater area. They are now receptive to the establishment of such a service in the region.

A theory for planning irrigation scheduling strategies under conditions of limited water supply was devised.

ACKNOWLEDGEMENTS

The research here reported was financed by the Water Research Commission and carried out under the research project entitled:

RESEARCH ON A WEATHER SERVICE FOR SCHEDULING THE IRRIGATION OF WINTER WHEAT IN THE ORANGE FREE STATE REGION

The evaluation committee responsible for the project consisted of the following members:

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The financial assistance received from the Water Research Commission and invaluable contributions made by the members of the evaluation committee are gratefully acknowledged.

Furthermore, the authors wish to convey their sincere gratitude to the following persons and institutions:

Mrs DAWN DE KLERK for typing the manuscript.

The many TECHNICAL ASSISTANTS whose arduous, time consuming task it was to collect the crop field data as well as undertake all data manipulation. Their contribution is greatly acknowledged and appreciation expressed for their unselfish acceptance of the inconvenience imposed while making the regular trips to Hartswater. The technical assistants recognized are: HENDRIK MYNHARD, JOHAN VAN RENSBURG, PETRUS STEYN, MICHAEL FLESLAND, GERHARD DE JONGH, NICO BARNARD, MARTHIE HOULTZHAUSEN, SUSANN GRIESSEL, THABO MARé, ANDRIES JACKSON and ANDRé JOUBERT.

Dr L K Oosthuizen (UOFS) for valuable assistance and guidance in establishing the theory for maximizing profits from wheat crop production under irrigation.

The cooperation of Mr Hugo Hamman, Chief Extension Officer of the Department of Agriculture (Experimental Station at Vaalharts) is herewith acknowledged for his exceptional assistance with distributing information during 1984. His office staff were most cooperative.

MR JAPIE SMIT is recognized. Without his cooperation and assistance the experiments could not have been undertaken. The telemeterized weather station was installed on his farm and he himself completed the telephonic connection thrice weekly to permit the transmission of weather data. It was due mainly to his encouragement and enthusiasm that so many farmers became involved in the project.

The large financial contribution of the University of the Orange Free State towards the purchasing of the lysimeter is gratefully acknowledged.

The Hydrological Research Unit of the Department of Water Affairs is thanked for providing the large bin for the lysimeter. In particular the efforts of Dr Peter MacRobert Reid in this regard are acknowledged.

Malcomess are acknowledged for providing the tractor and all the implements for cultivating the wheat.

The Bloemfontein Municipality were extremely sympathetic to the cause and made a special dispensation whereby the project was permitted to receive water during the drought when water restrictions were enforced throughout the entire area.

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APPENDIX I

MATHEMATICS

This section is aimed purely at documenting the elementary mathematics useful in various parts of the report.

DESCRIPTION OF ROOT DISTRIBUTION PATTERN

Let x denote the root mass per unit land surface area.

The defining equation for root mass distribution with soil depth (z) is

$$\delta x / \delta z = - ax$$

For the boundary conditions

x = Xo at a = 0, and x = 0 at a = ∞

The solution is $x = Xo\ e^{-az}$ ...(1)

Let ZEFF = Effective root depth i.e. currently the depth to which roots effectively extract water. Then the mean value is given by

$$\bar{x} = \int_{o}^{\infty} x .\ \delta z \ /\ ZEFF$$

$$= Xo\ /\ (ZEFF\ .\ a) \qquad ...(2)$$

Evaluation of a

Practical application of Eqn 1 requires knowledge of the value of a.

Let XT(z) = the total amount of roots contained in the soil profile to depth z.

Let XT(ZEFF) = the total root amount in the entire effective root zone.

Utilizing the assumption that XT(z) / XT(ZEFF) = 0,97 occurs at depth 0,97ZEFF it is possible to evaluate a.

Firstly

$$XT(ZEFF) = \int_0^{\infty} x\ z = Xo \int_0^{\infty} e^{-az}\ \delta z$$

$$XT(ZEFF) = Xo \int_0^{\infty} e^{-az}\ \delta z$$

$$= Xo\ [-\ 1/a\ e^{-az}]_0^{\infty}$$

$$= Xo/a[1\ -\ e^{-az}]_0^{\infty} \qquad ...(3)$$

$$= Xo/a \qquad ...(4)$$

From Eqn 3 using the boundary condition prescribed by the assumption

$XT(0,97ZEFF) = Xo/1[1 - e^{-a\ 0,97ZEFF}]$, and

$$XT(0,97ZEFF)) / (XT(ZEFF)) = (1 - e^{-a\ 0,97ZEFF}) = 0,97$$

$$\text{i.e. } e^{-a\ ZEFF} = 0,03$$

or

$$a = -(\ln[0,03]) / 0,97ZEFF \qquad \ldots(5)$$

Evaluation of root density within a given soil layer, xn

The amount of roots per unit of land surface found at depth z in the soil layer is given by

$$x = Xo\ e^{-az} \qquad \ldots(1)$$

Integration between two levels (zn1, zn2) = xn, the root amount in the nth layer

$$xn = \int_{zn1}^{zn2} x\ \delta z = Xo \int_{zn1}^{zn2} e^{-az}\ \delta z$$

$$= Xo[-1/k\ e^{-az}]_{zn1}^{zn2}$$

$$= Xo/k[e^{-azn2} - e^{-azn1}] \qquad \ldots(6)$$

Experimental evaluation of a

The value of a may also be found

(i) given Xo and XT using Eqn. 4. Thus

$$a = Xo/XT(ZEFF) \quad ...(8)$$

(ii) Alternatively should the mean value $\bar{x}$, ZEFF and Xo be known then

$$a = Xo/\bar{x}.ZEFF \quad ...(9)$$

may be used.

SOIL WATER DESORPTION CURVE

Consider, PSIS = soil water potential in kPa

V = volumetric water content in mm/m

Let $P = \ln(PSIS)$ ...(10)

A plot of P versus V for desorption curves appeared to be an exponential curve. Thus, the expression P = Po EXP(-mV) may be fitted to such curve.

Hence, if $P = Po\ EXP(-m.V)$ ...(11)

$P/Po = EXP(-m.V)$ ...(12)

and, $\ln(P/Po) = -mV$ ...(13)

Thus, $V = -1/m \ln(P.Po)$ ...(14)

Should the constants Po and m be known for the fitted curve; PSIS and V can be computed provided one or the other is known. Given V; the corresponding soil water potential may be computed using Eqn 10. And given P; the corresponding volumetric water content can be found using Eqn 14.

The fundamental equation describing the simulation curve is thus,

$$\ln(PSIS) = Po\ EXP(-mV) \qquad ..(15)$$

or

$$PSIS = EXP(Po\ EXP(-mV) \qquad ..(16)$$

<u>Determination of m and Po</u>

m and Po may be determined for a given curve by selecting two points on the curve with coordinates (P1, V1) and (P2, V2). The constant m is then calculated from

$$m = \ln(P1/P2)\ /\ (V2 - V1) \qquad ...(17)$$

The constant Po may be calculated using

$$Po = P/EXP(-mV) \qquad ...(18)$$

APPENDIX II SOIL PHYSICAL PROPERTIES

Soil physical characteristics as calculated with the Hutson equations (See Schulze, Hutson and Cass, 1985)

PLOT	DEPTH mm	CLAY %	V10 mm/m	V30 mm/m	V100 mm/m	V500 mm/m	V1500 mm/m
1	225	15,2	202	159	121	94	92
	525	18,2	214	172	133	108	104
	825	38	297	257	215	196	179
2	225	14,6	199	157	118	91	90
	525	16,4	207	164	126	100	97
	825	36,4	290	250	209	189	173
3	225	19,6	220	178	139	114	109
	525	28,4	257	216	175	153	143
	825	38,6	299	260	218	199	181
LYSIMETER							
TOP		17,6	212	170	131	105	101
BELOW		15,2	202	159	121	94	92

EQUATIONS : V10 = 0,1387 + 0,00416 * CLAY (%)
V30 = 0,0943 + 0,00428 * CLAY (%)
V100 = 0,0582 + 0,00413 * CLAY (%)
V500 = 0,0262 + 0,00447 * CLAY (%)
V1500 = 0,0344 + 0,00381 * CLAY (%)

where V is given in mm/mm.

Soil characteristics as computed in PUTU-9 from the Hutson equations.

DEPTH m	CLAY %	m	PO	V5 mm/m	V10 mm/m	V30 mm/m	V100 mm/m	V500 mm/m	V1500 mm/m	V1600 mm/m
1,225	15,2	,00927	14,84	240	201	159	126	94	76	75
1,525	18,2	,00941	17,16	252	214	172	140	108	91	90
1,825	38	,00988	43,02	333	296	257	226	196	179	178
2,225	14,6	,00913	14,25	239	200	157	124	91	73	72
2,525	16,4	,00941	15,92	244	206	164	132	100	83	82
2,825	36,4	,00988	40,15	326	289	250	219	189	172	172
3,225	19,6	,00941	18,16	258	220	178	146	114	97	96
3,525	28,4	,00956	26,82	294	257	216	184	153	136	135
3,825	38,6	,00988	44,31	336	299	260	229	199	182	181
LYSIMETER										
TOP	17,6	,00927	16,43	251	211	170	137	105	87	86
BELOW	15,2	,00927	14,84	240	201	159	126	94	76	75

Regression equations for the estimation of soil water retention and the persentage variation accounted for by the regression.

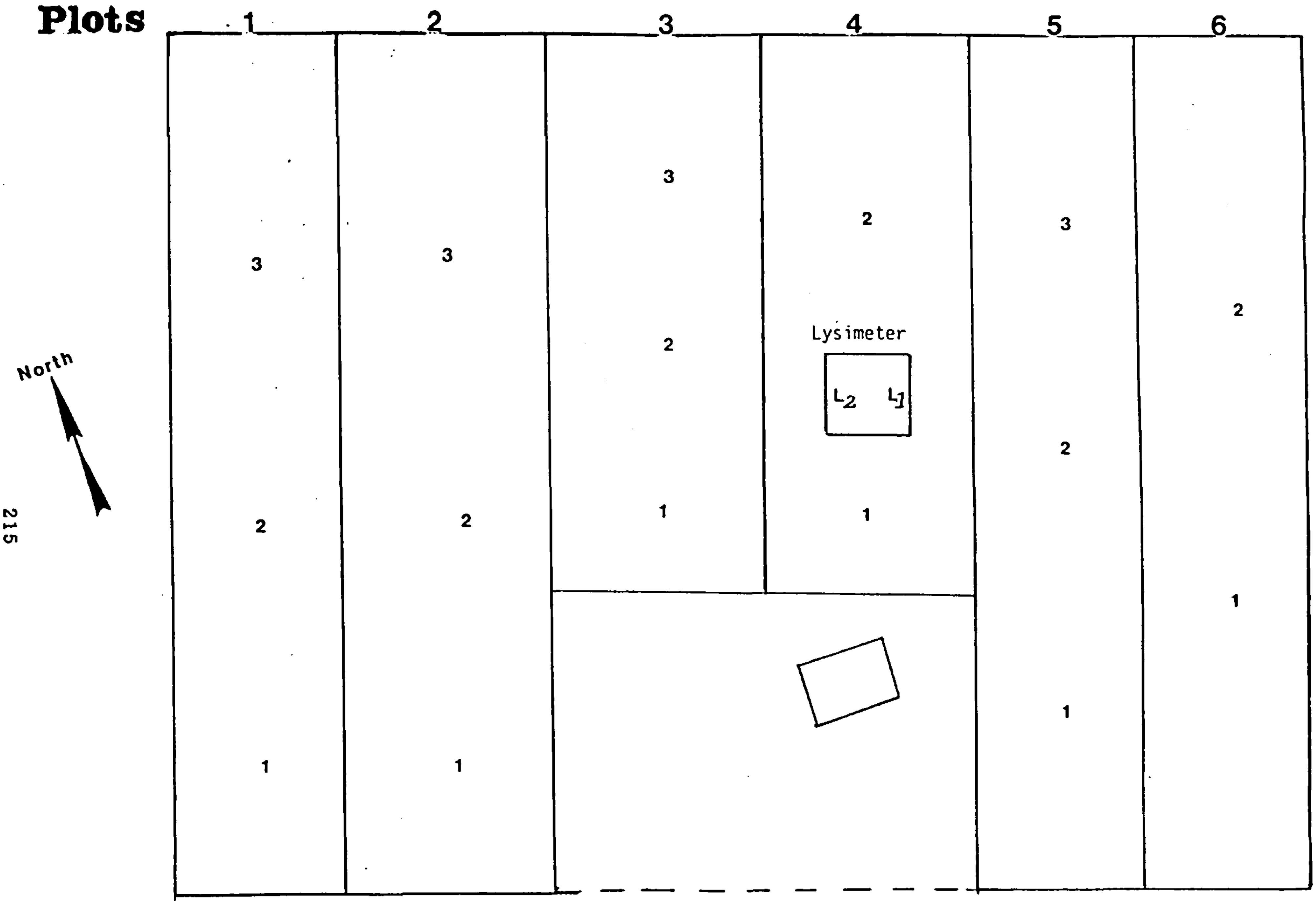
SOIL	EQUATION NO.	REGRESSION EQUATION	VARIANCE ACCOUNTED FOR (%)	S.E. OF ESTIMATES (%)
TOP	3.1	$\theta 5 = 21,11 + 0,44C + 1,29Si + 1,06OM - 11,91BD$	81	5,4
	3.2	$\theta 5 = 6,81 + 0,62C$	71	6,4
	3.3	$\theta 1500 = 15,26 + 0,28C + 0,05Si + 2,32OM - 10,6BD$	80	4,1
	3.4	$\theta 1500 = 3,02 + 0,44C$	66	5,2
	3.5	$\theta 1500 = -0,01 + 0,67C - 0,003C^2$	67	5,1
BELOW	3.6	$\theta 5 = 35,56 + 0,3C + 0,87Si - 19,8BD$	72	8,1
	3.7	$\theta 5 = 6,4 + 0,57C$	61	9,4
	3.8	$\theta 1500 = -1,93 + 0,31C + 0,59Si + 2,9BD$	81	4,2
	3.9	$\theta 1500 = 2,54 + 0,4C$	76	4,7
	3.10	$\theta 1500 = -3,54 + 0,78C - 0,004C^2$	79	4,4

The soil physical characteristics computed using the equations of Mottram (1985) in the PUTU-9 procedure.

DEPTH m	CLAY %	V5 mm/m	V10 mm/m	V30 mm/m	V500 mm/m	V1500 mm/m	V1600 mm/m	m	PO
1,225	15,2	251	227	201	161	150	149	,014	69,15
1,525	18,2	270	244	215	170	158	157	,013	61,79
1,825	38	515	470	421	345	324	323	,007	95,18
2,225	14,6	270	244	216	172	160	159	,013	66,02
2,525	16,6	261	235	207	163	151	150	,013	58,33
2,825	36,4	510	464	413	334	313	312	,007	80,90
3,225	19,6	306	278	247	200	187	186	,012	78,79
3,525	28,4	400	362	320	255	238	237	,009	67,50
3,825	36,4	523	478	428	352	331	330	,007	99,25
LYSIMETER									
TOP	17,6	271	246	219	176	165	164	,014	77,05
BELOW	15,2	240	216	189	148	137	136	,014	54,69

Approximate range in values measured by Neutron probe in the lysimeter in 1985.

DEPTH mm	PLOT1 V10 mm/m	PLOT1 V1500 mm/m	PLOT2 V10 mm/m	PLOT2 V1500 mm/m	PLOT3 V10 mm/m	PLOT3 V1500 mm/m	PLOT4 V10 mm/m	PLOT4 V1500 mm/m	PLOT5 V10 mm/m	PLOT5 V1500 mm/m
150	250	60	250	50	240	80	240	50	260	60
300	290	80	270	90	270	110	210	90	260	90
450	290	130	300	190	300	150	300	150	310	150
600	315	250	330	-	320	-	320	230	330	-
750	360	320	322	-	380	-	380	290	380	-
900	390	360	320	-	390	-	390	-	390	-
LYSIMETER										
150	190	90								
300	200	100								
450	200	90								
600	200	105								
750	200	105								
900	200	105								
1050	220	109								
1200	250	115								



Location of the pits at which sand,silt and clay percentages were measured at the experimental site on West Campus during 1985.

Sand, silt and clay percentages measured on the different irrigation plots on West Campus 1985 after the method of Day (1965).

PLOT	POSITION	DEPTH (mm)	SAND (%)	SILT (%)	CLAY (%)
1	1	100	81.46	16.8	1.3
		300	77.16	7.0	13.3
		500	73.98	4.5	22.2
1	2	100	60.69	7.8	31.1
		300	49.12	7.4	36.6
		500	47.72	6.2	44.2
1	3	100	56.06	9.6	34.9
		300	46.61	10.01	39.7
		500	44.06	10.0	38.7
2	1	100	84.27	2.8	8.4
		300	76.73	12.6	18.4
		500	71.22	4.2	25.2
2	2	100	61.2	7.4	30.6
		300	60.1	6.8	33.0
		500	55.43	6.3	34.7
2	3	100	48.45	6.0	35.2
		300	46.39	12.0	37.4
		500	51.89	10.3	32.5
3	1	100	80.85	7.1	9.3
		300	74.91	4.6	20.7
		500	70.20	5.6	24.6
3	2	100	54.6	7.0	34.2
		300	48.51	6.0	43.2
		500	46.26	4.5	47.7
3	3	100	63.66	11.2	26.8
		300	46.22	8.2	38.6
		500	45.57	8.8	38.4
4	1	100	73.02	4.0	22.8
		300	54.58	4.2	40.8
		500	49.2	3.6	46.6
4	2	100	44.60	7.0	48.0
		300	41.18	8.0	52.4
		500	40.32	5.8	53.0

PLOT	POSITION	DEPTH (mm)	SAND (%)	SILT (%)	CLAY (%)
5	1	100	82.84	3.0	15.2
		300	77.86	2.6	18.2
		500	41.3	3.6	54.6
5	2	100	81.12	4.0	14.6
		300	81.58	4.0	16.4
		500	60.18	2.4	36.4
5	3	100	76.64	7.4	19.6
		300	73.34	6.4	28.4
		500	55.32	5.2	38.6
6	1	100	81.50	4.0	8.2
		300	59.68	3.2	37.6
		500	54.78	4.2	40.6
6	2	100	81.9	8.4	14.0
		300	75.72	4.6	18.0
		500	62.48	4.2	32.8
LYSIMETER	1	100	82.20	10.2	18.4
		300	82.10	1.0	19.6
		500	81.22	3.2	14.8
				II6	
	2	100	81.38	2.6	16.4
		300	81.92	3.2	15.8
		500	80.32	4.0	15.6

Soil physical characteristics for the five farms at Hartswater.

FARM	NO	CLAY (%)	SILT (%)	SAND COARSE (%)	SAND MED (%)	SAND FINE (%)	ORGANIC MATERIAL (%)	m	Po
A Subsoil		12	2	2,98	20,22	63,84	2,1	,00913	12,89
A Subsoil	1	14	4	2,84	16,64	63,94	1,7	,00927	14,17
	2	14,4	4	2,22	18,58	62,58	1,6	,00927	14,43
	3	16	2	3,80	18,16	61,2	2,0	,00927	15,4
B Subsoil	1	24	2	1,8	14,92	59,36	2,45	,00941	21,71
	2	27	3	1,54	14	56,66	2,90	,00956	25,32
	3	16	2	2,0	17,22	65,72	1,6	,00927	15,4
	4	14	2	2,08	17,54	65,66	1,4	,00927	14,17
	5	10	1	2,48	17,42	68,48	1,4	,00913	11,87
B Topsoil	1	13	1	2,82	19,96	63,96	1,8	,00913	13,37
	2	10	2	5,0	22	62	1,6	,00913	11,87
	3	22	3,6	2,28	16	58	1,6	,00956	20,52
	4	22,4	3,6	1,66	14,76	60	0,98	,00941	20,33
B Subsoil		12	2	2,16	22,72	61,72	0,8	,00913	12,89
B	1	10	2	5,44	22,4	61,02	1,0	,00913	11,87
	2	10,4	2,6	2,56	16,16	68,44	2,33	,00913	12,09
B Topsoil	1	12	2	4,96	23,48	59,9	2,09	,00913	12,89
	2	14	4	3,28	16,84	62,76	2,6	,00926	14,17
E Subsoil	1	14	5,6	10,56	19,64	52,88	2,2	,00927	14,17
	2	15	1	11,18	20,62	55,74	2,4	,00913	14,51
	3	16	2	11,44	21,64	52,28	2,2	,00927	15,4
E Topsoil	1	10	2	13,64	28,44	48,26	1,7	,00913	11,87
	2	9	1	7,54	26,64	56,94	1,5	,00899	11,24
	3	11	2,6	12,64	23,58	52,60	2,0	,00913	12,31
D Subsoil	1	8	1,6	1,82	26,14	65,78	1,1	,00899	10,84
	2	8	2	1,62	20,0	69,98	1,1	,00899	10,84
	3	8	2	3,46	23,16	65,68	1,0	,00899	10,84
D Topsoil	1								
	2	8	2	1,46	28,36	62,64	1,2	,00899	10,84
	3	8	0	2,68	27,46	63,0	1,1	,00899	10,84
	4	8	1	1,94	20,6	68,84	1,3	,00899	10,84

FARM	NO	CLAY (%)	SILT (%)	SAND COARSE (%)	MED (%)	FINE (%)	ORGANIC MATERIAL (%)	m	Po
C	1	9,6	0,4	4,0	22,14	66,88	1,1	,00913	11,66
Subsoil	2	7	1	4,52	23,78	65,4	1,05	,00899	10,00
	3	10	3	1,88	18,28	70,0	1,11	,00913	11,87
C	1	5,6	2,4	4,36	28,48	61,78	1,0	,00899	9,82
Topsoil	2	7	3	4,88	23,28	65,46	1,4	,00899	10,37
	3	6	2	5,10	26,60	62,90	1,1	,00899	10,00

APPENDIX III

a. DIE SIMULERING VAN PLANTHOOGTE VAN KORING ONDER BESPROEIING

<u>Doel</u>

Die ontwikkeling van 'n model wat die planthoogte van besproeiingskoring (cv:SST44) akkuraat simuleer.

<u>Metodes en resultate</u>

Waarnemings van planthoogte op verskeie plekke en oor verskeie jare (Tabel III.1) is gebruik om 'n model te ontwikkel wat planthoogte simuleer.

Akkumulatiewe hitte-eenhede na plant(Akkhe) en dae na plant (DOG) is oorweeg vir die primêre inset. Deur middel van statistiese passing op gemete planthoogtes (tot en met blomdatum) is lineêre, eksponensiële, logistiese en polinomiese verwantskappe tussen elk van bogenoemde veranderlikes en planthoogte ondersoek. Die kleinste standaardfout van beraming (Sb = 74 mm) is verkry met 'n derde graad polinoom met DOG as insetveranderlike:

$$Hoog = 12.74 - 0.882*DOG + 0.0891*DOG^2 - 2.09*10^{(-4)}*DOG^3 \quad ..(III.1)$$

waar Hoog - planthoogte (mm)

DOG - dae na plant

Vgl. III.1 en gemete planthoogtes word grafies in Fig. III.1 geillustreer.

In die PUTU 9-model word hierdie verwantskap aangewend om die aerodinamiese konduktansie te beraam. 'n Fout van ,1m in die skatting van planthoogte sal lei tot 'n fout so klein as 10% in die beraming van aerodinamiese konduktansie.

Gedurende die vegetatiewe groeifase word die planthoogte volgens Vgl.III.1 bereken. Gedurende die reproduktiewe stadium (die tydperk na groeistadium 75 volgens die sisteem van Human <u>et. al</u>.,1981) bly die hoogte konstant op die hoogte wat bereik is op groeistadium 75. Wanneer Akkhe as insetveranderlike gebruik word, lewer 'n liniêre verwantskap die beste passing met Sb = 112 mm:

$$\text{Hoog} = -10.34 + 1.482*\text{Akkhe} \qquad ..(III.2)$$

<u>Gevolgtrekkings</u>

Vir die doeleindes van besproeiingskedulering in die Vrystaatstreek m.b.v. PUTU 9-reeks modelle, is Vgl.III.1 'n bevredigende model vir die simulering van planthoogte oor die groeiseisoen.

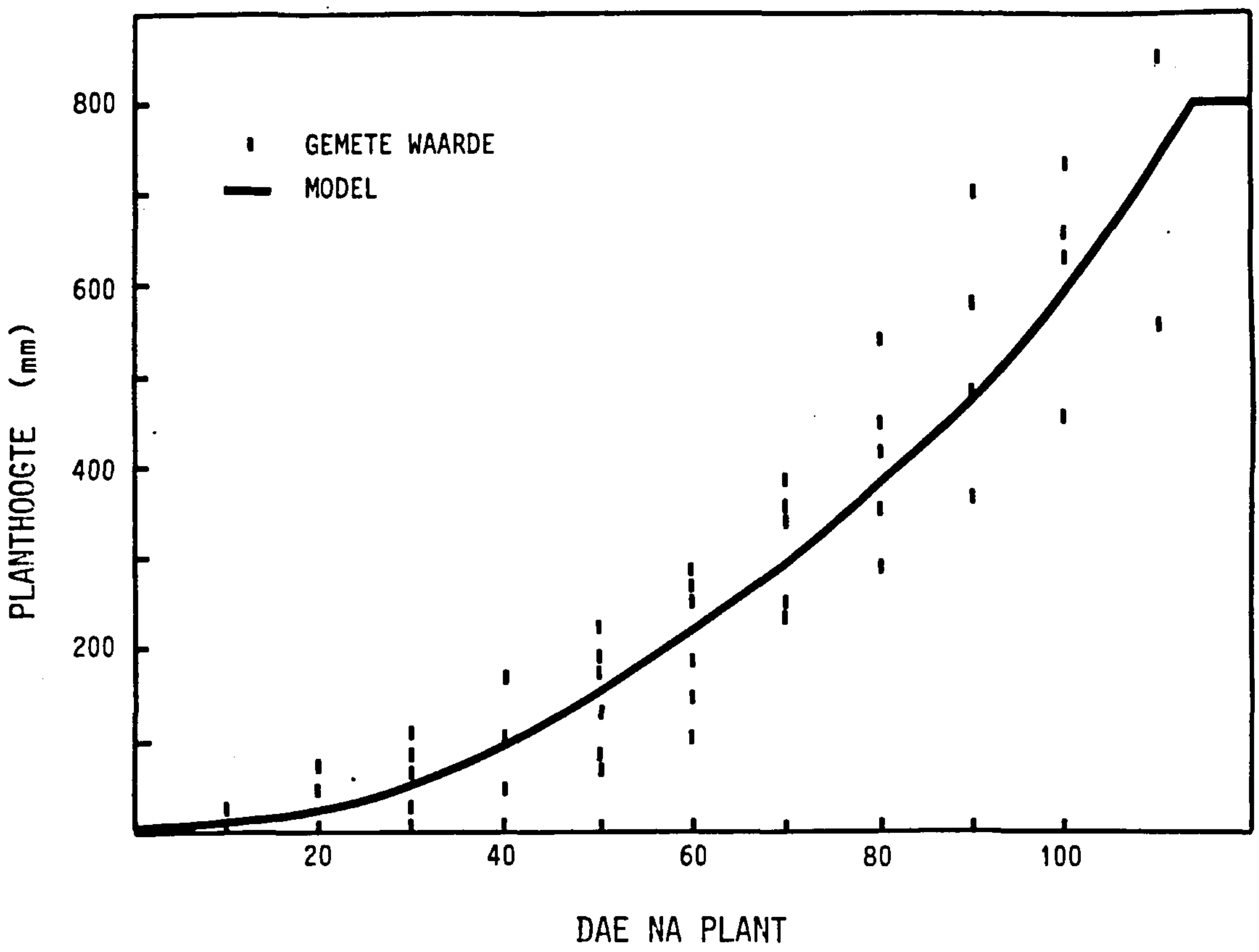


FIG. III.1. - Gemete planthoogtes van verskeie aanplantings oor die groeiseisoen en die kromme (Vgl. III.I) wat planthoogte oor die vegetatiewe groeistadium simuleer.

TABEL III.1 - Plantdatums, blomdatums en plantdigthede van die verskillende aanplantings wat gebruik is om die model vir die berekening van planthoogte te ontwikkel.

PLEK	LIGGING		JAAR	PLANT DATUM	BLOM- DATUM	PLANT- DIGTHIED
	S	O		(kalenderdag)		(plante/m^2)
UOVS	29 7'	26 11'	1985	184	287	220
UOVS	29 7'	26 11'	1984	183	285	220
UOVS	29 7'	24 50'	1980	165	268	140
HAW	27 57'	24 50'	1983	164	263	258
HAW	27 57'	24 50'	1982	167	271	383
HAW	27 57'	24 50'	1982	176	271	233
HAW	27 57'	24 50'	1981	161	270	220
JKEMP	27 55'	24 50'	1981	159	272	220

UOVS - UOVS WES-KAMPUS
HAW - HARTSWATER
JKEMP - JAN KEMPDORP

b. VERFYNING VAN 'N BLAARGROEIMODEL VIR KORING ONDER BESPROEIING

Inleiding

Blaaroppervlakte het 'n groot invloed op die tempo van waterverbruik deur 'n koringgewas. Die akkurate skatting daarvan is dus noodsaaklik vir susksesvolle besproeiingskedulering. Daar is dus gepoog om 'n bestaande blaargroeimodel(de Jager et.al.,1982) te verbeter.

Teorie

Die teorie van die bestaande sub-model in PUTU-9 word volledig verduidelik in De Jager *et. al*. (1982). Kortliks simuleer die model blaargroei met behulp van die volgende vergelykings:

$$Dlap = He * Q10 * Fw \quad ..(III.3)$$

$$Lap = Lap + Dlap \quad ..(III.4)$$

$$Boi = Lap * Npl \quad ..(III.5)$$

$$He = (Tmx + Tmin)/2 - Bo \quad \text{en } Tmx < To \quad ..(III.6)$$

waar, Dlap - die daaglikse toename in blaararea per plant (m^2/plant)

Lap - die blaaroppervakte per plant (m^2/plant)

Boi - die blaaroppervakte per oppervlakte grond (m^2/m^2)

He - die daaglikse hitte-eenhede bo 8 °C (°C)

Npl - die plantdigtheid (plante/m^2)

Q10 - groeitempo koëffisiënt (m^2/(°C plant))

Fw - die berekende waterstremmingsfaktor (De Jager et. al., 1982)

Tmx - daaglikse maksimum temperatuur tot 'n maksimum van 20 °C (°C)

Tmin - daaglikse minimum temepratuur (°C)

Bo - basistemperatuur vir blaargroei (8 °C)

To - hoogste lugtemperatuur vir normale blaargroei (20 °C)

Die waarde van Q10 wissel na gelang van die groeistadium van die gewas, soos volg:

Q10 = 2 * 10^(-5) vir 0 < DOG <= 60 (stoelstadium) ..(III.7)

Q10 = 2,5 * 10^(-4) vir 60<DOG<=Bld-Pld (pypstadium) ..(III.8)

Q10 = -1.5 * 10^(-4) vir DOG>Bld-Pld (reproduktiewe stadium) ..(III.9)

waar DOG - die aantal dae na plant

Bld - blomdatum (kalenderdag)

Pld - plantdatum (kalenderdag)

Die gebruik van bogenoemde model vir besproeiingskedulering het sekere leemtes aan die lig gebring. In teenstelling met die werklikheid, word positiewe blaargroei gesimuleer nadat die vlagblaar reeds volwasse is. Die aanvang van die pypstadium (waartydens die groeitempo die hoogste is), is konstant geneem as 60 dae na plant ongeag weerstoestande tydens die stoelstadium. Die model het ook nie onderlinge kompetisie vir lig by hoë blaaroppervlaktes in aanmerking geneem nie.

Verfyning

Die akkurate berekening van die tydsduurtes van die verskillende groeistadia is noodsaaklik omdat die verskillende Q10-waardes vir elke groeistadium grootliks verskil. Uit gemete waardes van planthoogte en blaaroppervlaktes kon die werklike duurte van die stoelstadium beraam word. Hieruit het dit geblyk dat die gewas 'n kritieke hoeveelheid hitte-eenhede (Akkhec) akkumuleer voordat die einde van die stoelstadium bereik word (groeistadium 39 volgens die sisteem van Human et.al., 1981). Hierdie hoeveelheid hang onder andere af van die vernalisasietekort (Verndef) wat die gewas ondervind het. 'n Lineêre verwantskap tussen Akkhec en Verndef is ontwikkel:

$$\text{Akkhec} = 145 + \text{Vcon} * \text{Verndef} \qquad ..(\text{III}.10)$$

$$\text{Verndef} = \text{Vernc} - \text{Akkke} \qquad ..(\text{III}.11)$$

waar Akkhec - kritieke hoeveelheid akkumulatiewe hitte-eenhede (^{o}C.d)

Verndef - vernalisasietekort (^{o}C.d)

Vcon - konstante (^{o}C hitte/ ^{o}C koue)

Vernc - kouebehoefte van SST44 (^{o}C.d)

Akkke - Akkumulatiewe koue-eenhede in stoelstadium (^{o}C.d) (sien Vgl. III.12)

Die waarde van Vcon is 21,8 ^{o}C/ ^{o}C wat verkry is d.m.v. die beste passing van diė een aanplanting waar Verndef > 0 was.

Die daaglikse koue verantwoordelik vir vernalisasie is soos volg bereken:

$$Ke = Bv - (Tmaks+Tmin)/2 \quad en \quad 0 < Ke < 2 \qquad ..(III.12)$$

waar Bv - basistemperatuur vir vernalisasie (8 ^{o}C)

Tmaks - daaglikse maksimum temperatuur (^{o}C)

Tmin - daaglikse minimum temperatuur (^{o}C)

Ke - koue-eenhede (^{o}C)

Die waarde van Bv is geneem as 8 ^{o}C, met ander woorde byvoorbeeld is die skeidingspunt tussen hitte vir groei (sien Vgl. III.6) en koue vir vernalisasie (sien Vgl. III.12). Hierdie verwantskap word geillustreer in Fig. III.2.

Volgens Maas en Arkin (1980) het enige daaglikse gemiddelde temperatuur onder 6 ^{o}C dieselfde vernalisasie-effek - vandaar die boonste limiet vir Ke.

Vanuit die relatiewe koue-behoeftes van koringcultivars (Joubert,1984) en die kwantitatiewe kouebehoeftes van Scheepers69, SST101 en Belinda (Joubert,1982) is beraam dat SST44 'n kouebehoefte (Verndef) van 7,4 (^{o}C.d) het.

Die duurte van die pypstadium (groeistadia 40-59 volgens Human <u>et.al</u>., 1981) kon nie susksesvol gesimuleer word nie. 'n Volledige ondersoek na die fenologie van verskeie cultivars word in die vooruitsig gestel. Tot tyd en wyl, word die waargenome datum van aarverskyning as inset in die model gebruik om die einde van die pypstadium aan te dui (sien Vgls. III.14 en III.15).

$Q10 = 2 * 10^{(-5)}$ vir $Akkhe < Akkhec$ (stoelstadium) ..(III.13)

$Q10 = 2,5 * 10^{(-4)}$ vir $DOG < Epd-Pld$ (pypstadium) ..(III.14)

$Q10 = -1,5*10^{(-4)}$ vir $DOG > Epd-Pld$ (reproduktiewe stadium) ..(III.15)

Waar Epd - datum van die einde van die pypstadium (kalenderdag).

Om kompetisie by hoë blaaroppervlaktes in ag te neem, is Vgl. III.3 verander na Vgl. III.16 en Vgls. III.17 en III.18 is adisioneel in die model ingesluit. Kompetisie vind plaas by blaaroppervlaktes groter as Boio. Die daaglikse toename in blaaroppervlakte per plant onder hierdie toestande word dan gereduseer eweredig tot die verhouding tussen die optimum plantdigtheid (Nplo) en die werklike plantdigtheid (Npl). Die waarde van Nplo is geneem as 140 plante/m^2 aangesien die Q10 waardes verkry is by hierdie plantdigtheid. 'n Waarde van 2,3 vir Boio het die beste passing met gemete waardes gelewer.

$$Dlap = He * Q10 * Fw * Komp \quad ..(III.16)$$

$$Komp = Nplo/Npl \text{ vir } Npl>Nplo \text{ en } Boi>Boio \quad ..(III.17)$$

$$Komp = 1 \text{ vir } Npl < Nplo \text{ en/of } Boi<=Boio \quad ..(III.18)$$

$$Fw = 1 \text{ vir } DOG >= Epd - Pld \quad ..(III.19)$$

Vgls. III.4, III.5 en III.6 word net so behou vir die verbeterde model.

<u>Verifiering</u>

Die model is getoets teen gemete waardes van blaaroppervlakte-indeks van vier seisoene op verskeie lokaliteite (sien Tabel III.3). Hierdie aanplantings het geen waterstremming ondervind nie. 'n Gladde kromme is deur die gemete waardes getrek om monsteringsvariasie te elimineer. Die gewasfaktor (Fle) van Ritchie (1972) is bereken vanaf Boi waardes van bogenoemde kromme. Beide Boi en Fle waardes van elke tien dae is vergelyk met ooreenstemmende berekende waardes deur middel van verskeie statistiese analises. Wanneer beide gemete en berekende waardes van Fle = 1 was, is dit geïgnoreer. Die simulering van blaargroei tydens die die reproduktiewe fase is nie getoets nie weens 'n gebrek aan waarnemings. Resultate van die statistiese toetse wat die akkuraatheid van die model weerspieël word in Tabel III.2 gegee.

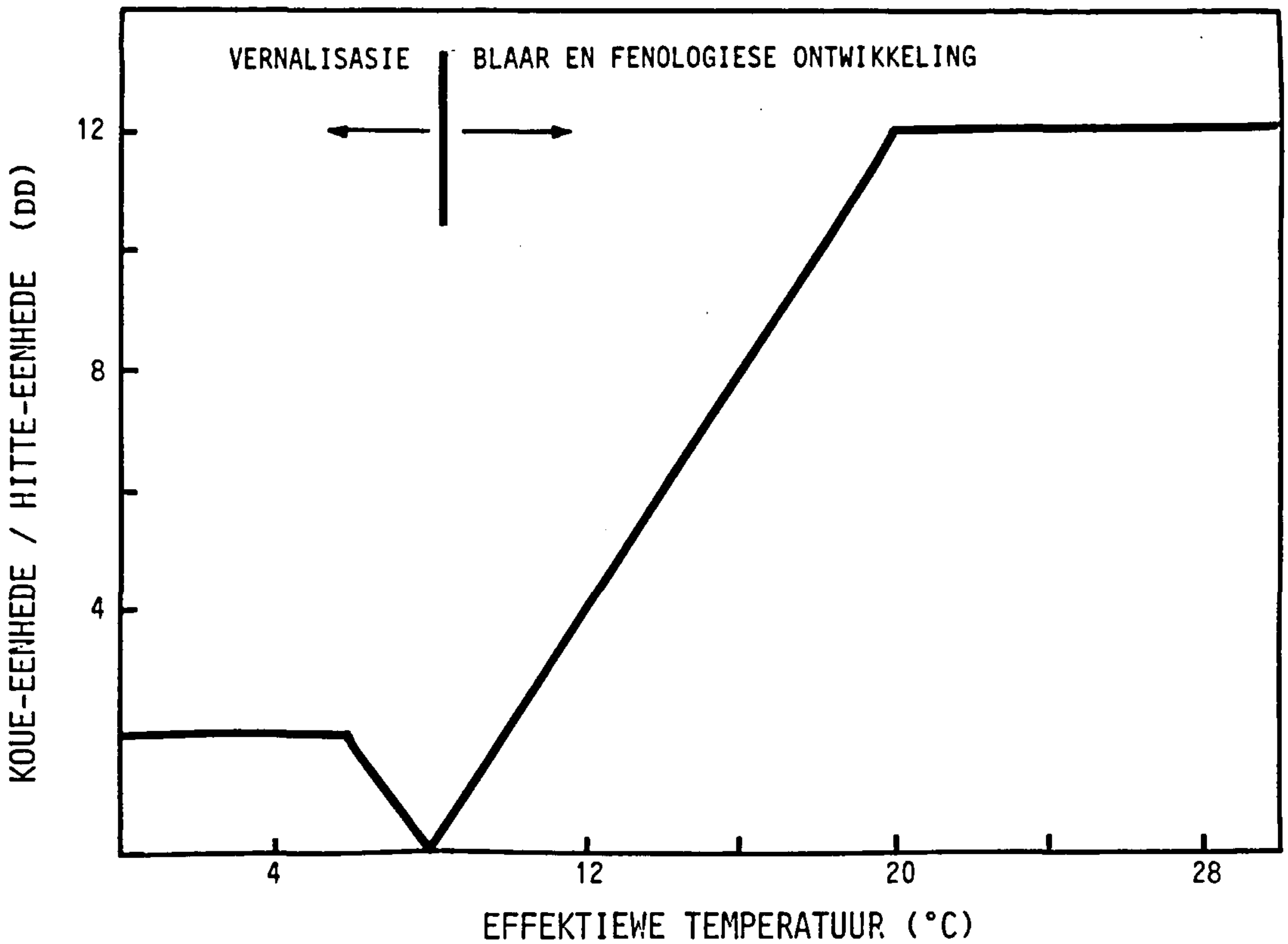


FIG. III.2 - Die verwantskap tussen temperatuur en koue-eenhede vir vernalisasie en hitte-eenhede vir blaargroei soos gebruik in die verbeterde model.

TABEL III.2 - Die waardes van verskeie statistiese parameters wat verkry is met die toets tussen gemete en berekende waardes van blaaroppervlak-indeks (BOI) en die gewas faktor (Fle).

Statistiese parameter		BOI	Fle
		(m^2/m^2)	
b		1.02	0.78
c		0.04	0.09
r		0.93	0.83
d		0.96	0.91
diff		0.69	0.12
se	(%)	11	29

b - helling van die regressie tussen berekende en gemete waardes

c - afsnit van regressie tussen gemete en berekende waardes

r - korrelasie koëffisiënt

d - akkuraatheidsindeks (Willmott, 1982)

diff - gemiddelde absolute verskil tussen gemete en berekende waardes

se - sistematiese fout as'n persentasie van die totale fout (Willmott, 1982)

TABEL III.3 - Plantdatums, datums van die einde van pypstadium en plantdigthede van aanplantings wat gebruik is vir die verifiering van die model.

PLEK	JAAR	PLANTDATUM	DATUM VAN EINDE PYP	PLANT-DIGTHEID
		kalenderdag		plante/m^2
UOVS	1985	184	276	220
UOVS	1984	183	277	220
UOVS	1980	165	261	140
HAW	1983	164	249	258
HAW	1982	167	257	383
HAW	1982	176	257	233
HAW	1981	161	263	220
JKEMP	1981	159	253	220

1 - Temperature vanaf kalenderdag 164-208 was nie beskikbaar nie en langtermyn gemiddeldes is vir modellopies gebruik.

2 - Datum van einde van pypstadium is beraam.

APPENDIX IV - LISTING: PUTU 9.86


```
5   '*****************************************************************
10     'PUTU9-86        NAAM:PUTU9-86        OP DISK:PROGRAM #2 (a)
20      LPRINT "Latest up-date on    1986.08.19 "
25  '*****************************************************************
26  '
27  LPRINT  "         FIELD WATER CAPACITY AT -10 kPa         "
28  '
29  '
30     OPTION BASE 1
40     DIM X(366,8),GMT(12),GMR(12),GMS(12),GME(12),MONL(12),MEND(12),DOYMES(12
50     '
60     GOSUB 2500                                       'MEAN DATA
62     GOSUB 15000                                      'FUNCTIONS
64     GOSUB 9500                                       'INITIAL CONDITIONS
72     GOSUB 10500                                      'WEATHER DATA INPUT
75     GOSUB 3100                                       'PARAMETERS
80     GOSUB 10000                                      'ZERO
85     GOSUB 5000                                       'TITLE PAGE
86     '
90                    '**************************
100                   'BEGINNING OF CALCULATION
101                   '**************************
130    '
170    FOR D = BEGIN TO FINISH
172    '
180       GOSUB 5500                                    'ENVIRONMENTAL VARIABLES
190       GOSUB 6000                                    'WATER BALANCE
200    IF STAGE > 1 THEN 230
210       GOSUB 1400                                    'PREREST PERIOD
220       GOTO  540
230    IF STAGE > 2 THEN 260
240       GOSUB 1500                                    'REST PERIOD
250       GOTO  520
260    IF STAGE > 3 THEN 290
270       GOSUB 1600                                    'TILLERING
280       GOTO  500
290    IF STAGE > 4 THEN 320
300       GOSUB 1700                                    'STEM EXTENTION
310       GOTO  500
320    IF STAGE >5  THEN 350                            'BOOTING
330       GOSUB 1800
340       GOTO  500
350    IF STAGE > 6 THEN 380
360       GOSUB 1900                                    'ANTHESIS
370       GOTO 500
380    IF STAGE > 7 THEN 410
390       GOSUB 2000                                    'GRAIN FILLING
400       GOTO 500
410    '  STAGE 8
420       GOSUB 2100                                    'RIPENING
430    '
500       GOSUB 12800                                   'ASSIMILATION
510       GOSUB 11500                                   'TRANSLOCATION
520       GOSUB 12000                                   'TOTALS
530       GOSUB 7000                                    'WRITE RESULTS
```

```
535    '  IF D=FINISH THEN GOSUB 14100          'WRITE CARRY OVER FILE
540    NEXT  D
542    D = D - 1         :  YEAR = YEAR + 1       :  GOSUB 13900
543    '
550    GOSUB 7590                               'RECORD RESULTS ON DOY 365/6
557    GOTO 610
560    GOSUB 2400                               'RESET
600    GOSUB 10000                              'ZERO
610    GOSUB 9600                               'MID-SEASON INITIAL CONDITIONS
614    IF QQ <> 1 THEN 620
615    BEGIN = 1
616    GOTO 630
620    GOSUB 10500                              'WEATHER DATA
630    GOSUB 5400                               'TABLE HEADING
640    GOTO  150
650    '
660    '****************************************************************
1400   '                  "Stage 1 pre-rest period"
1405   '****************************************************************
1410   IF STAGE = 1 AND D=BEGIN THEN  PRINT "GROWTH STAGE 1 PRE-REST PERIOD"
1415   IF D < JR THEN 1480
1420   STAGE=2
1430   HU=0
1450   TREE=0
1460   GOSUB 10000                            ' ZERO
1470   LPRINT "  GROWTH STAGE 2 - REST PERIOD       DOY   ";D
1480   RETURN
1490   '
1500   '                  "Stage 2 rest period"
1505   '****************************************************************
1510   IF D<JP THEN 1585
1515   STAGE=3
1520   LPRINT "  Total rainfall in rest period=";TREE
1525   DOG = 0
1530   TREE=0
1535   TTRANS = 0
1540   TPTRANS = 0
1541   GOSUB 9800               ' TO ESTABLISH SOIL WATER CONTENT IF SO WISHED
1542   CB=SEEDMAS*NPL  * 10^4
1543   C = CB     :  CL = CB
1545   Q = .8
1550   Q10=2*10^(-5)
1555   KY=.2 : KY=1
1560   HU=0
1565   HUC = HUCO
1570   GOSUB 12500                  'MEANS
1575   GOSUB 10000                  'ZERO
1580   LPRINT "  GROWTH STAGE 3 - TILLERING PERIOD "
1585   RETURN
1590   '
1595   '****************************************************************
1600   '                  "Stage 3 tillering period"
1605   '****************************************************************
1606     IF HU>=HUCO AND VTEL=0 THEN VERNDEF=CUC-CU :VTEL=1: HUC=HUCO+CON1*VERNDE
F: IF HUC<HUCO THEN HUC=HUCO
1610   IF HU<HUC THEN 1665 : 'IF D < ENDTIL THEN 1665
1619   STAGE=4
1620   Q = .8
1625   Q10=2.5*10^(-4)
1627   RT = TTRANS/TPTRANS
1630   YRED(STAGE-1)=  KY*(1-RT)
1635   KY=.2 : 'KY=1
1637   LPRINT USING "  YRED=### TTRANS=### TPTRANS=### TLYS= ### C=##### BL/C=.
 GL/C=.## SL/C=.##";YRED(STAGE-1)*100;TTRANS;TPTRANS;TLYS;C;BL/C;GL/C;SL/C
1638 LPRINT USING "  DEEPERC=####     TSOILVAP=####   WUSE=####   TAW=####  ";
EPERC;TSEVAP;WUSE;TAW
1640   TTRANS=0  :TPTRANS=0 : TLYS=0
1645   LPRINT "  GROWTH STAGE 4 STEM EXTENTION PERIOD"
1650   ENDTIL=D
1660   RETURN
1665   REM
1670   GOSUB 10850                                       'CROP HEIGHT
1672   GOSUB 5700                                        'PSIC
1673   GOSUB 10900                                       'LEAFGROWTH
1674   GOSUB 10800                                       'HAIL
1675   BETA=DELLAP*NPL*SPL
1680   RHO=.1*DMG                                        'TRANSLOCATE TO ROOTS
1681   PHI=.1*DMG                                       ' TRANSLOCATE TO STEMS
1682   ALPHA=0                                          ' TRANSLOCATE TO GRAIN
1683   THETA = DMG-(ALPHA+PHI+BETA+RHO)                 ' RESERVES IN STUBBLE
1684   RETURN
1685   '
1690   '****************************************************************
1700   '                        Stage 4 stem extention
1705   '****************************************************************
1710   IF D < ENDEXT THEN 1756
1715   STAGE=5
1720   ENDBOOT=ENDEXT+5
1725   Q10=-1.5*10^(-4)
1727   RT = TTRANS/TPTRANS
1730   YRED(STAGE-1)=  KY*(1-RT)
1732   LPRINT USING "  YRED=### TTRANS=### TPTRANS=### TLYS= ### C=##### BL/C=.
GL/C=.## SL/C=.##";YRED(STAGE-1)*100;TTRANS;TPTRANS;TLYS;C;BL/C;GL/C;SL/C
1733 LPRINT USING "  DEEPERC=####     TSOILVAP=####   WUSE=####   TAW=####  ";
EPERC;TSEVAP;WUSE;TAW
1735   TTRANS=0  :TPTRANS=0 : TLYS=0
1740   KY=.65 : 'KY=1
1745   LPRINT "  GROWTH STAGE 5 BOOTING "
1750   RETURN
1756   '
1759   GOSUB 5700: GOSUB 10900: GOSUB 10800  : GOSUB 10850  'SEE LINES 1670-16
1760   BETA=DELLAP*NPL*SPL
1765   PHI=.2*DMG
1770   RHO=.1*DMG
1775   ALPHA=0
1780   THETA=DMG-(ALPHA+BETA+PHI+RHO)
1785   RETURN
1790   '
1795   '****************************************************************
1800   '                   "Stage 5   booting"
1805   '****************************************************************
1810   IF D < ENDBOOT THEN 1860
1815   STAGE = 6
1820   ENDANT=ENDBOOT+10
1821   RT = TTRANS/TPTRANS
```

```
1822  YRED(STAGE-1)=  KY*(1-RT)
1823  LPRINT USING "  YRED=### TTRANS=### TPTRANS=### TLYS= ### C=##### BL/C=.##
 GL/C=.## SL/C=.##";YRED(STAGE-1)*100;TTRANS;TPTRANS;TLYS;C;BL/C;GL/C;SL/C
1824 LPRINT USING "  DEEPERC=####      TSOILVAP=####   WUSE=####   TAW=####  HT=.
## ";DEEPERC;TSEVAP;WUSE;TAW;HT
1826  TTRANS=0  :TPTRANS=0 : TLYS=0
1830  KY=.65 : 'KY=1
1840  LPRINT "GROWTH STAGE 6 ANTHESIS"
1850  RETURN
1860  '
1864  GOSUB 5700: GOSUB 10900: GOSUB 10800  : GOSUB 10850  'SEE LINES 1670-1683
1865  BETA=0
1870  PHI=.2*DMG
1875  RHO=.1*DMG
1880  ALPHA=0
1885  THETA=DMG-(ALPHA+BETA+PHI+RHO)
1890  RETURN
1895  '***************************************************************
1900  '                      Stage 6  anthesis
1910  '***************************************************************
1920  IF D<ENDANT THEN 1970
1925  STAGE = 7
1930  ENDFILL=ENDANT+35
1942  RT = TTRANS/TPTRANS
1943  YRED(STAGE-1)=  KY*(1-RT)
1944  LPRINT USING "  YRED=### TTRANS=### TPTRANS=### TLYS= ### C=##### BL/C=.##
 GL/C=.## SL/C=.##";YRED(STAGE-1)*100;TTRANS;TPTRANS;TLYS;C;BL/C;GL/C;SL/C
1945 LPRINT USING "  DEEPERC=####      TSOILVAP=####   WUSE=####   TAW=####  HT=.
## ";DEEPERC;TSEVAP;WUSE;TAW;HT
1947  TTRANS=0  :TPTRANS=0 : TLYS=0
1950  KY=.55 : 'KY=1
1957  LPRINT "GROWTH STAGE 7  GRAIN FILLING"
1960  RETURN
1970  '
1976  GOSUB 5700: GOSUB 10900: GOSUB 10800 : GOSUB 10850   'SEE LINES 1670-1683
1980  BETA=0:PHI=0:RHO=0  :ALPHA=DMG
1985  THETA=DMG-(ALPHA+BETA+PHI+RHO)
1990  RETURN
1995  '****************************************************************
2000  '                      STAGE 7   Grain filling
2010  '****************************************************************
2020  IF D<ENDFILL THEN 2055
2025  STAGE = 8
2030  ENDRIPE=ENDFILL+10
2032  RT = TTRANS/TPTRANS
2035  YRED(STAGE-1)=  KY*(1-RT)
2037  LPRINT USING "  YRED=### TTRANS=### TPTRANS=### TLYS= ### C=##### BL/C=.##
 GL/C=.## SL/C=.##";YRED(STAGE-1)*100;TTRANS;TPTRANS;TLYS;C;BL/C;GL/C;SL/C
2038 LPRINT USING "  DEEPERC=####      TSOILVAP=####   WUSE=####   TAW=####  ";DE
EPERC;TSEVAP;WUSE;TAW
2039  TTRANS=0  :TPTRANS=0 : TLYS=0
2045  LPRINT "GROWTH STAGE 8 RIPENING "
2050  RETURN
2055  '
2058  GOSUB 5700: GOSUB 10900: GOSUB 10800                  'SEE LINES 1670-1683
2059  IF LAI<0 THEN LAI=0
2060  BETA=0:PHI=0:RHO=0:ALPHA=DMG
2070  THETA=DMG-(ALPHA+BETA+PHI+RHO)
2080  RETURN
2090  '****************************************************************
2100  '                      STAGE 8   RIPENING
2105  '******************************************************************
2110  IF D<ENDRIPE THEN 2153
2115  Y=YO*(1-(YRED(3)+YRED(4)+YRED(5)+YRED(6)+YRED(7)))
2120  LPRINT "   Environmental potential yield for "; YEAR;" ";:LPRINT USING
       "#####";Y;:LPRINT " kg/ha"
2125  LPRINT USING "TOTAL DEEP PERCOLATION  #### , EVAPORATION FROM THE SOIL
RFACE ####   AND  TOTAL WATER USE  ####";DEEPERC;TSEVAP;WUSE
2130  INPUT "Do you wish to repeat the calculation for a further season(Y/N)
      ANSWER$
2140  IF ANSWER$ <>"Y" THEN 16000
2150  GOTO  560
2153  '
2155  GOSUB 5700 : GOSUB 10900
2156  GOSUB 10800
2160  ALPHA=0:BETA=0:PHI=0:RHO=0:THETA=0
2170  RETURN
2180  '
2190  '*****************************************************************
2400  'RESET ALL STATUS VAR. TO ZERO AND COEFFICIENTS ,RE-ESTABLISH INITIAL
2401  '    CONDITIONS AND REST PHASE
2402  '*****************************************************************
2410  TP     = 0
2420  HUPREV = 0
2430  HU     = 0
2440  SINKF  = 1
2450  DREP   = 0
2460  DOG    = 0
2470  TREE   = 0
2480  STAGE  = 2
2485  BL=0:GL=0:CL=0:SL=0:RL=0:C=0:CB=0:CA=0
2490  X1=0:X2=0:X3=0:X4=0:X5=0:X6=0:X7=0:X8=0:X9=0
2499  '*****************************************************************
2500  '                          MEAN  DATA
2510  '***************************************************************
2530  DATA 31,28,31,30,31,30,31,31,30,31,30,31
2540  FOR I=1 TO 12
2550  READ MONL(I)     : 'PRINT MONL(I)
2560  NEXT I
2570  DATA 22.9,21.9,19.8,15.6,11.4,8.1,8.5,10.6,14.6,18,20.1,22.1
2580  FOR I=1 TO 12
2590  READ GMT(I)      : 'PRINT GMT(I)
2600  NEXT I
2610  DATA 9.3,8.4,7.9,7.9,8.1,7.8,8.3,9.1,9,9.2,9.8,9.9
2620  FOR I=1 TO 12
2630  READ GMS(I)      : 'PRINT GMS(I)
2640  NEXT I
2650  DATA 84.6,81.9,76.7,53.7,23.5,7.0,90.0,90.0,90.0,90.0,90.0,68.1
2660  FOR I=1 TO 12
2670  READ GMR(I)      : 'PRINT GMR(I)
2671  NEXT I
2675  DATA 12,11,10,9,8,5,5,8,9,10,11,12
2676  FOR I=1 TO 12
2677  READ GME(I)      : 'PRINT GME(I)
2678  NEXT I
2686  'INPUT "NAME OF FILE ON WHICH TO STORE 1-WATER CONTENTS AND 2-CROP
       VARIABLES ";SOWAT$,GRO$
2687  SOWAT$ = "THETAV"  :  GRO$ = "PHYS"
       KILL SOWAT$       :  KILL GRO$
2689  OPEN GRO$    FOR APPEND AS #2   :  OPEN SOWAT$   FOR APPEND AS #3
```

```
2690  RETURN
2691  '*****************************************************************
2700  '     DISTRIBUTION OF INFILTRATION WATER THROUGH SOIL PROFILE
2710  '*****************************************************************
2830  IF X(D,3) = 0 AND X(D,6) = 0 THEN 3090
2840  RUNOF = .2
2850  INFIL = X(D,3)+IR
2860  IF INFIL < 50 THEN RUNOF = .1
2870  IF INFIL < 25 THEN RUNOF = .05
2880  IF INFIL < 15 THEN RUNOF = 0
2890  INFIL = (X(D,3)+X(D,6)) * (1-RUNOF)
2910  W(1)=W(1)+INFIL-SOILVAP
2920  'LPRINT W(1)
2930  IF W(1)<=W01(1) THEN 2960
2940  PERC(1)=W(1)-W01(1)
2950  W(1)=W01(1)
2960  V(1) = W(1)/DZRT
2970  PSIS(1) = FNTION15(P0(1),M(1),V(1))
2980  'PRINT W(1),V(1),PERC(1),PSIS(1)
2985  IF INFIL=0 THEN 3090
2990  FOR L=2 TO 9
3000  W(L)=W(L)+PERC(L-1)
3010  IF W(L)<W01(L) THEN 3050
3020  PERC(L) = W(L) - W01(L)
3030  W(L) = W01(L)
3050  V(L) = W(L)/DZRT
3060  PSIS(L) = FNTION15(P0(L),M(L),V(L))
3070  'PRINT USING "######";W(L);V(L);PERC(L);PSIS(L)
3080  NEXT L
3082  DEEPERC = DEEPERC + PERC(9)
3084  'LPRINT "DEEP PERCOLATION " ;DEEPERC
3086  FOR L=1 TO 9
3087  PERC(L)=0
3088  NEXT L
3090  RETURN
3099  '**********************************************************************
3100  '                          PARAMETERS
3101  '**********************************************************************
3110 'GOSUB 14000
3120  TPAW=0
3130  FOR L=1 TO 9
3140  PERC(L)=0
3141  V01(L)=FNTION16(M(L),2.3  ,P0(L))  '1.609 FOR V0 AT 5 kPa
3142  V15(L)=FNTION16(M(L),7.3,P0(L))
3143  V16(L)=FNTION16(M(L),7.4,P0(L))
3144  W01(L)=V01(L)*DZRT
3145  W15(L)=V15(L)*DZRT
3146  W16(L)=V16(L)*DZRT
3147  PAW(L)=W01(L)-W16(L)
3148  TPAW=TPAW+PAW(L)
3149  'PRINT W15(L),W01(L),W(L),W16(L),TPAW
3150  NEXT L
3200  SPL  = 500           'SPECIFIC LEAF RATIO kg/ha
3210  '                     KAISER....SPL=50g/m^2=.05kg/m^2  500kg/ha LEAFAREA
3220  SEEDMAS=.03*10^(-3)               'kg/seed
3270  TO = 25
3275 VTEL=0
3280  BO = 8
3290  HUMX=20              'DAILY MAX TEMP FOR CALC OF HEAT UNITS
3294  CUC = 7.4             'MINIMUM COLD UNITS<8 REQUIRED TO END TILLERING
3296  CON1 = 21.8          'ADDITIONAL DD PER UNIT CUDEFICIT DD/CU
3320  COO=.012
3330  EFFMAX=20            'PHOTO EFFICIENCY (%)
3340  FE=68*10^(-9)        'PHOTO CHEMICAL EKWIVALENT   kg\J
3360  WEQ=40               'kg/(ha mm)
3370 WEQ=2*WEQ               '  DM
3380 YO=7000                 ' KG/Ha
3411  RGR = .018           'RATE OF VERTICAL ROOT GROWTH RATE  m/d
3412  AP = 2.1             '% OF TOTAL ROOTS FOUND BELOW 0.97
3413  AP = AP/100
3414  RMO = 100            'kg/(ha pl)
3416  KSPO = -1.2*10^(-3)   'MAX CONDUCTANCE OF ROOT ZONE  mm/(d kPa m pl)
3417  KSPO = KSPO*DZRT*NPL
3420  RETURN
3430  '
5000  '**************************************************************
5010  '                          TITLE PAGE
5020  '**************************************************************
5030  LPRINT TAB(7);"PUTU9 IRRIGATION SCHEDULING OF WHEAT"
5035 'LPRINT "                                     Run date : ";DATE$;"  T.
: ";TIME$
5110 'LPRINT
5130  LPRINT TAB(7);N$
5140 'LPRINT
5150  LPRINT TAB(10),"PLANT POPULATION ";TAB(38),"CULTIVAR";TAB(55),"PLANTIN.
TE"
5160  LPRINT TAB(16);NPL;" (/m^2)";TAB(45);C$;TAB(57);PDAY;"/";PMONTH;"/";YE
5165  LPRINT TAB( 6),"EXTENTION ENDED ON DOY ";ENDEXT
5170 'LPRINT
5180  LPRINT TAB(10),"SOIL DESCRIPTION:";W$
5210  LPRINT TAB(10),"SOIL MOISTURE (mm/m)"
5230  LPRINT TAB(15);"MAXIMUM";TAB(30);"MINIMUM";TAB(40);"INITIAL";TAB(50);"
CTIVE ROOTING DEPTH"
5240  LPRINT USING "             ###          ###        ###          #.
;V01(2);V15(2);VINIT(2);ZEFFO;
5242  LPRINT "m"
5250  '
5300  '**************************************************************
5350  '                          TABLE HEADING
5400  '**************************************************************
5410 'LPRINT
5420  LPRINT TAB(7);YEAR
5430  LPRINT
5440  LPRINT "  DOY   FH   LAI  IR RAIN PERC    WATER POTENTIAL    HU   Em
  Es  Elys"
5443  LPRINT"                                    S2   S3   ST   L"
5445  LPRINT "       (%)   x10   (%)     (mm)      (MPa*100)      (DD)     (
0)       "
5450  RETURN
5460  '
5470   **************************************************************
5500  '           ENVIRONMENTAL VARIABLES AND LIMITING FACTORS
5510  '**************************************************************
5520  NMX= FNDLENGTH(D)                                  ' MAX DAYLENGTH
5530  SO = FNMJD(D)                                      ' DLY POSS  RAD
5555  KT = X(D,4)
```

```
5560  RFDM = FNDLYR(SO,KT,NMX)                              ' DLY MEAN RFD
5580  GOSUB 8500                                            ' TEMP
5590  FS = FNRAD(LAI)                                       ' RADIATION FACTOR
5600  GOSUB 9000                                            'REF EVAPOTRANSPIRATION
5610  PAR = .5 * RFDM
5620  RETURN
5690  '*************************************************************
5700  '               CRITICAL LEAF WATER POTENTIAL
5702  '*************************************************************
5710  PSIC = -1600 - 11.7 * (DOG-50)
5720  IF PSIC > -1600 THEN PSIC = -1600
5730  IF PSIC < -2300 THEN PSIC = -2300
5740  RETURN
5805  '*************************************************************
6000  '                           WATER BALANCE
6020  '*************************************************************
6030  GOSUB 13000      'ROOT DEVELOPMENT
6040  GOSUB 8000       'SOIL WATER POTENTIAL
6050  GOSUB 13300      'SOIL-ROOT CONDUCTANCE,
6052                   'WATER POTENTIALS EACH SOIL LAYER, PSIleaf, FH
6054                   'EXTRACT WATER FROM EACH LAYER
6055  FW = FH
6056  IF FW >1 THEN FW=1
6057  IF FW <0 THEN FW=0
6058  'PRINT USING "######.##";FH;FW
6060  GOSUB 2700       'RE-WET SOIL
6490  RETURN
6491  '*******************************************************************
6500  '                                   DOY
6510  '*******************************************************************
6520  IF DAYS=366 THEN MONL(2)=29
6530  JI=0
6540  FOR M=1 TO MONTH
6550  IF M = 1 THEN 6570
6560  JI=JI+MONL(M-1)
6570  NEXT M
6580  DOY =JI+DAY
6590  MONL(2)=28
6591  RETURN
6592  '
6999  '****************************************************************
7000  '           TO RECORD DAILY VALUES AND STORE ON TO DISK
7112  '********************************************************************
7115  PRINT #3,USING "#### ";D,DOG,
7130  PRINT #3,USING "##.### ";-PSIS(1)/1000,-PSIS(2)/1000,-PSIS(3)/1000,-PSIS(4
      )/1000,-PSIS(5)/1000,-PSIS(6)/1000,-PSIS(7)/1000,-PSIS(8)/1000,-PSIS(9)/10
00,
7132  PRINT #3,USING "##.### ";-PSIST/1000,-PSIL/1000,
7135  PRINT #3, USING "##### ";V(1),V(2),V(3),V(4),V(5),V(6),V(7),V(8),V(9),
7137  PRINT #3, USING "##### ";PAWL(1),PAWL(2),PAWL(3),PAWL(4),PAWL(5),PAWL(6),P
AWL(7),PAWL(8),PAWL(9),
7142  PRINT #3,USING "#### ";PPAW
7500  '
7510  '
7520  'IF JX<>10  THEN 7690
7530  IF STAGE=1 THEN 7690
7540  IF STAGE=2 THEN 7690
7590  '
```

```
7592  GOSUB 12500                                  'MEANS
7595  ' IF X(D,7) <> 22 THEN 7690
7598 IF PSIL>-800 THEN FUDGE=-700 ELSE FUDGE=0
7600 LPRINT USING "#####";D;FW*100;LAI*10;X(D,6);X(D,3);DEEPERC;PSIS(2)/10;PS
     3)/10;PSIST/10;(PSIL+FUDGE)/10;HU/10;PV*10;TRANS*10;SOILVAP*10;X(D,8)*10
7605  '
7610  PRINT #2, USING "#### ";D,DOG,FW*100,LAI*10,BL,RL,CL,GL,C,SL,DMG,TREE,
      TRANS*10,PTRANS*10,(TRANS+SOILVAP)/PV*100,X(D,8)/PV*100,YRED*100,Y,YO,K
7611  '
7612  'GOSUB 10000                                  'ZERO
7690  RETURN
7700  '*****************************************************************
8000  '                        SOILWATER POTENTIAL
8001  '*****************************************************************
8010  FOR L=1 TO 9
8020  PSIS(L) = FNTION15(PO(L),M(L),V(L))
8025  'PRINT USING "######";PSIS(L);
8030  NEXT L
8040  RETURN
8498  '
8499  '*****************************************************************
8500  '                        TEMPRATURE ROUTINES
8501  '*****************************************************************
8510  IF X(D,1)= -99.9 THEN X(D,1)=GMT
8520  IF X(D,2)= -99.9 THEN X(D,2)=GMT
8530  T=(X(D,1)+X(D,2))/2                                  'TEMPERATURE, HEAT
8540  UPRT=X(D,1)
8550  IF X(D,1)>HUMX THEN UPRT=HUMX
8560  EFFGT=(UPRT+X(D,2))/2
8570  IF EFFGT<BO THEN EFFGT=BO
8572  HUPREV=HU
8575  DELHU = EFFGT - BO
8580  HU=HU+(EFFGT-BO)                                     'HEAT UNITS
8582  DELCU = BO-(X(D,1)+X(D,2))/2
8584  IF DELCU <=  0 THEN DELCU=0
8586  IF DELCU >2 THEN  DELCU = 2
8588  CU = CU + DELCU
8600  FTP=FNTION6(T,TO)
8610  TNITE=X(D,1)/3+X(D,2)/2
8630  RETURN
8631  '
8640  '*****************************************************************
9000  '                         TOTAL EVAPORATION
9001  '*****************************************************************
9010  ' Calculates potential and crop evaporation
9020  H=.5* RFDM
9030  Z= FNTION8(T)
9040  FLE=FNTION9(LAI)                                     ' VEG COVER FACTOR
9042  IF STAGE>7 OR STAGE=7 THEN FLE=.9
9044  IF DOG < ENDANT+31 OR  STAGE<7 THEN 9050
9046  FLE = .9-.062*(DOG-(ENDANT+31))
9050  IF FLE <.1 THEN FLE=.1
9060  IF FLE >.9 THEN FLE=.9
9070  PV=FNTION10(Z,H) * 10^6
9075  PV = X(D,5)
9080  PTRANS = FLE * PV
9090  V1DEF = VO1(1)-V(1)
```

```
9100  IF VIDEF < 0 THEN  VIDEF = 0
9110  FG = FNTION21(VIDEF)
9120  SOILVAP = FG*(1-FLE)*X(D,7):  'PRINT USING "#####.##";FG;VIDEF;SOILVAP
9480  RETURN
9490  '*******************************************************************
9500  '                          INITIAL CONDITIONS
9505  '*******************************************************************
9510   INPUT "NAME OF CARRY OVER FILE......................";CO$
9515   OPEN "I",#1,CO$
9520   GOSUB 13900           ' ESTABLISH THE DOY ON WHICH THE MONTHS END
9540   INPUT #1,N$                     'STATION
9545   INPUT #1,W$                     'SOIL DESCRIPTION
9550   INPUT #1,C$                     'WHEAT CULTIVAR
9552   INPUT #1,DOY,DOG,PMONTH,PDAY,JP,STAGE,BEGIN,FINISH
9560   INPUT #1,NPL                    'PLANT POPULATION/m^2
9565   INPUT #1,ENDEXT,ENDTIL          'STEM EXTENTION AND TILLERING ENDED ON DOY
9567   INPUT #1,HUCO                   'CRIT MIN HEAT REQUIRED-END TILLERING
9568   HUC=HUCO
9570   INPUT #1,ZEFFO,DZRT,HT,LAI,HU,CU,TTRANS,TPTRANS,WUSE,TSEVAP,DEEPERC,RT
9572   INPUT #1,YO,Y,YEAR
9576   YO  = YO*1000  :  Y = Y*1000   :   YEAR = YEAR*1000
9580   FOR L = 1 TO 9
9583   INPUT #1,VINIT(L)               'INITIAL SOIL MOISTURE (Volumetric mm/m)
9585   W(L) = VINIT(L)*DZRT
9587   V(L) = VINIT(L)
9591   NEXT L
9595   FOR L = 1 TO 9
9600   INPUT #1,M(L)
9605   NEXT L
9610   FOR L = 1 TO 9
9615   INPUT #1,PO(L)
9620   NEXT L
9625   CLOSE #1
9630   CLS
9640   LOCATE    6,20
9650   PRINT USING "  YOU ARE IN YEAR  ####";YEAR
9655   MONTH = PMONTH   :   DAY = PDAY
9670   DAYS = 365
9680   IF YEAR MOD 4=0 THEN DAYS=366
9690   GOSUB 6500
9695   JP=DOY
9700   PRINT "  PLANTING DOY      ";JP
9710   PRINT "  GROWTH STAGE      ";STAGE
9760   INPUT " DO YOU WISH TO ALTER ANY INITIAL CONDITIONS (Y/N)";ANSW$
9780   IF ANSW$ = "Y" THEN GOSUB 14250
9790   RETURN
9799  '*******************************************************************
9800  '                           SOILWATER CONTENT
9801  '*******************************************************************
9810  QQQ=0: INPUT "ENTER 9 IF YOU WISH TO ESTABLISH SOILWATER AT PLANTING ";QQQ
9820  IF QQQ=0 THEN 9870
9830  FOR L=1 TO 9
9831  PRINT "LAYER No. ";L
9832  INPUT "INITIAL SOIL WATER     ";VINIT(L)
9840  W(L)=VINIT(L)*DZRT
9850  V(L) = VINIT(L)
9860  NEXT L
9870  RETURN
9999  '*******************************************************************
10000  '                          SET ALL VARIABLES TO ZERO
10001  '*******************************************************************
10020  JX=0
10030  TREEN=0
10040  TTOT=0
10050  TDREIN=0
10060  SRFD=0
10070  SP=0
10080  PSI2=0
10085  TPSIL = 0
10090  AL=0
10100  VMIN=W01(9)/DZRT
10110  TFG=0
10120  'TTRANS=0
10130  'TPTRANS=0
10140  TVER=0
10150  TPV=0
10160  TBWP=0
10170  TGWP=0
10180  TF=0
10190  TFI=0
10200  TFW=0
10205  TFH=0
10210  TFTP=0
10220  TDMG=0
10230  TFC=0
10240  TFLE=0
10250  TFTR=0
10260  TFTL=0
10270  TEFF=0
10280  TFFMAX=0
10290  TRESP=0
10300  TMAIN=0
10310  ASSIM=0
10320  TP=0
10330  TDMG=0
10340  DMG=0
10350  RETURN
10351  '
10360  '*******************************************************************
10500  '                          TO READ DATA
10501  '*******************************************************************
10502 INPUT " IN ORDER TO GENERATE SIMPLE DATA SERIES ENTER 1  ";QQ
10503  IF QQ = 1 THEN 11000        ' DATA GENERATOR
10504  INPUT"IN ORDER TO READ IRRIGATION FILE ENTER 1 ";QQQ
10510  INPUT "Name of WEATHER data file eg. B: 2008-83 ",D$
10540  OPEN "I",#1,D$
10542  IF D$="B:1985" THEN START=60  ELSE START =61
10550  FOR I=START TO BEGIN - 1 + 4   ' DATALEER HET 4 OPSKRIFTE
10560  INPUT #1,K$
10570  NEXT I
```

```
10575  INPUT "ENTER NUMBER OF MONTH IN WHICH YOU START  ",M
10580  FOR D = BEGIN TO FINISH
10590  INPUT #1,X$
10600  P=LEN(X$)
10610  'P<48 THEN X$=" "+X$   : GOTO 10600
10620  X(D,1)=VAL(MID$(X$,7,6))
10630  X(D,2)=VAL(MID$(X$,13,6))
10640  X(D,3)=VAL(MID$(X$,19,6))
10642  X(D,7)=VAL(MID$(X$,31,6))
10644  X(D,8)=VAL(MID$(X$,43,6))
10650  X(D,4)=VAL(MID$(X$,25,6))
10651 X(D,5)=VAL(MID$(X$,37,6))
10652  IF D<=MEND(M) THEN 10660
10653  M=M+1
10660  FOR E=1 TO 7:IF E=4 OR E=6 THEN 10710
10670  IF X(D,E)<>-99.9 THEN 10710
10680  XMISS=X(D,E)
10685  PRINT USING " Missing value of element ## on day #### ";E;D
10690  X(D,E)=X(D-1,E)
10700  IF E=3 THEN X(D,E)=0
10710  NEXT E
10720  IF X(D,4)=-99.9 THEN X(D,4) = GMS(M) : PRINT USING " Missing value of ele
ment  4 on day #### ";D
10722  IF X(D,8)=-99.9 AND D<233 THEN X(D,8) = 2       : PRINT USING " Missing va
lue of element  8 on day #### ";D
10723  IF X(D,8)=-99.9 AND D>=233 THEN X(D,8) = 4      : PRINT USING " Missing v
alue of element  8 on day #### ";D
10730   PRINT USING "###.##";M;D,X(D,1),X(D,2),X(D,3),X(D,4),X(D,5),X(D,7),X(D,8
)
10740  NEXT D:CLOSE #1 : IF  QQQ<>1 THEN 10760 ELSE CLS:PRINT "LYSIMETER = L  :
 CONTROL=K  :  1=1  : 2=2  :  3=3  :  4=4"
10741 INPUT "NAME OF IRRIGATION FILE AND PLOT NO. eg B:IRRIG.85,L";IRRIG$,ANTW$
10742 OPEN "I",#1,IRRIG$
10743 INPUT  #1,X$
10744 DOYIRR=VAL(MID$(X$,1,3)):IF DOYIRR=0 THEN 10759
10745 IF ANTW$="L" THEN CHARA=7
10746 IF ANTW$="K" THEN CHARA=25
10747 IF ANTW$="1" THEN CHARA=13
10748 IF ANTW$="2" THEN CHARA=19
10749 IF ANTW$="3" THEN CHARA=31
10750 IF ANTW$="4" THEN CHARA=37
10751 X(DOYIRR,6)=VAL(MID$(X$,CHARA,6)):PRINT DOYIRR,X(DOYIRR,6):GOTO 10743
10759 CLOSE #1
10760  RETURN
10799  '*****************************************************************
10800  '                             HAIL
10801  '*****************************************************************
10805  HAILPC=0
10810  FOR I=1 TO DOYSHAIL
10820  IF D<> DOYHAIL(I) THEN
10830  HAILPC=HAILP(I)
10840  NEXT I
10845  RETURN
10849  '*********************************************************************
10850  '                  CROP HEIGHT
10851  '*********************************************************************
10860  DELHT=FNTION19(DOG,FW) - FNTION19(DOG-1,FW)
10862  HT = HT + DELHT
10870  IF HT>1 THEN HT=1
10880  RETURN
10899  '*******************************************************************
10900  '                            LEAF GROWTH
10901  '*******************************************************************
10907 FLGRO=FW
10908 IF Q10<0 AND FLGRO<1 THEN FLGRO=1
10910  DELLAP=FNTION20(Q10,DELHU,FLGRO)
10920  IF LAI>=2.3 AND NPL>=140 THEN DELLAP=DELLAP*FNLRED(NPL)
10930  LAP=LAP + DELLAP * NPL
10940  LAI=LAP
10950  IF LAI < 0 THEN LAI = 0
10960  IF LAI > 8.5 THEN LAI = 8.5
10970  RETURN
10999  '**********************************************************************
11000  '                             SIMPLE WEATHER GENERATOR
11001  '**********************************************************************
11070  I=1
11080  FOR D=1 TO DAYS
11090  IF D<=MEND(I) THEN  11110
11100  I=I+1
11110  X(D,1)=GMT(I)
11120  X(D,2)=GMT(I)
11130  X(D,3)=0
11140  X(D,4)=GMS(I)
11150  X(D,5)=GME(I)
11160  IF D MOD 10=0 THEN X(D,3)=GMR(I)/3
11170  NEXT  D
11180  RETURN
11498  '
11499  '**********************************************************************
11500  '                                TRANSLOCATION
11501  '**********************************************************************
11530  GL=GL+ALPHA
11540  BL=BL+BETA
11550  CL=CL+PHI
11560  RL=RL+RHO
11580  SL=SL+THETA
11590  TLAI=BL/SPL
11600  GD=GD+X8*GL
11610  CD=CD+X9*CL
11620  BD=BD+X1*BL
11630  SD=SD+X2*SL
11640  RD=RD+X3*RL
11650  CA=GL+CL+BL+ SL+GD+CD+BD+SD
11660  CB=RL+RD
11670  C=CA+CB
11680  TR=X4*GD+X5*CD+X6*BD+X7*SD
11690  DA=TR+GD+CD+BD+SD
11700  DB=RD
11710  'NB C INCL STAND DEAD
11770  RETURN
11998  '
11999  '**********************************************************************
12000  '                                  SUB TOTALS
12001  '**********************************************************************
12010  JX=JX+1
```

```
12020  IF STAGE >2 THEN DOG = DOG+1
12030 'TRFD=TRFD+RFD
12040 'TPV=TPV+PV
12050  TSEVAP=TSEVAP+SOILVAP
12060 'SRFD=SRFD+RFD
12070  'RAINFALL
12080  TREEN=TREEN+X(D,3)
12090  TREE=TREE+X(D,3)
12100  'TREEN=total rainfall for appropriate period
12110  'TREE=total rainfall up to present date
12120  'TTOT=total temp for appropriate meaning interval
12130  TDMG=TDMG+DMG
12140  TTOT=TTOT+T
12150 'TFG=TFG+FG
12160  TTRANS=TTRANS+TRANS        '****************************
12170  TPTRANS=TPTRANS+PTRANS   '****************************
12172 TLYS=TLYS+X(D,8)
12175  WUSE = WUSE + SOILVAP +TRANS
12176  DEFPERC = DEEPPERC + PERC(9)
12180 'TBWP=TBWP+BWP
12190 'TGWP=TGWP+GWP
12210 'PSI2=PSI2+PSIST                              'SUM SOILWATER
12215 'TPSIL=TPSIL+PSIL
12220 'TFS=TFS+FS
12230 'TF=TF+F
12240 'TFTP=TFTP+FTP
12250 'TFW=TFW+FW
12260 'TFLE=TFLE+FLE
12270 'TFTR=TFTR+FTR
12280 'TFC=TFC+FC
12290 'TFT=TFT+FT
12300 'TFH=TFH+FH
12310 'TFFMAX=TFFMAX+EFFMAX
12320 'TEFF=TEFF+EFF
12330  TP=TP+P                                        'TOT PHO
12340 'TRESP=TRESP+RESP
12350 'TMAIN=TMAIN+MAINR
12360 'ASSIM=ASSIM+DMG
12400  RETURN
12401  '
12499  '*******************************************************************
12500  '                                  MEANS
12501  '*******************************************************************
12510  TTOT=TTOT/JX
12520  SRFD=SRFD/JX
12530  PSI2=PSI2/JX
12535  PSILM=TPSIL/JX
12540  TFS=TFS/JX
12550  TFW=TFW/JX
12555  TFH=TFH/JX
12560  TFC=TFC/JX
12570  TF=TF/JX
12580  TFTL=TFTL/JX
12590  TFTR=TFTR/JX
12600  TFLE=TFLE/JX
```

```
12610  TFFMAX=TFFMAX/JX
12620  TEFF=TEFF/JX
12630  TRFD=TRFD/JX
12640  TDMG=TDMG/JX
12650  MASSIM=ASSIM/JX
12660  TP=TP/JX
12670  TPV=TPV/JX
12690  TREEN=TREEN/JX
12700  SRFD=SRFD/10^6
12761  IF STAGE < 3 THEN 12780
12762  FRACG=GL/C
12763  FRACL=BL/C
12764  FRACS=SL/C
12765  FRACS=SL/C
12766  FRACR=RL/C
12770  TBWP=TBWP/JX
12777  TBWP=TBWP/JX
12780  TGWP=TGWP/JX
12790  RETURN
12791  '
12800  '*******************************************************************
12810  '                  PHOTOSYNTHYSIS AND ASSIMILATION
12820  '*******************************************************************
12830  F=FH * FTP  * FS                  'EFFICIENCY FACTOR
12840  EFF = EFFMAX * F
12850  EFF = EFF /100
12860  EFS = EFF * PAR * 10^6 ' J/(m^2 d) EFFECTIVE RADIATION FOR PHOTOSYNTH
12870  P = EFS * FE * Q
12880  P = P * 10^4             ' kg/(ha d)
12885  P = WEQ *TRANS
12890  SYNR=FNTION12(P)                  'SYNT RESP
12900  MAINR=FNTION13(COO,TNITE,C)
12920  RESP=SYNR+MAINR
12930  DMG=P-RESP
12935  'LPRINT USING "#####.##";FH;FTP;FS;SYNR;MAINR;DMG;P;RESP
12940  RETURN
12986  '*******************************************************************
13000  '                        ROOT DEVELOPMENT
13001  '*******************************************************************
13010  IF DOG = 0 THEN 13175
13015  IF STAGE > 7  THEN 13175
13020  RDEVF=RGR*DOG
13030  ZEFF=RDEVF
13040  IF RDEVF > ZEFFO THEN ZEFF = ZEFFO
13050  A=-LOG(AP)/(.97*RDEVF)
13060  ZBOT=0
13070  RMASS=0
13080  FOR L=1 TO 9
13090  RPROP(L)=0
13100  ZTOP=ZBOT
13110  ZBOT=L*DZRT
13120  RPROP(L)=(EXP(-A*ZTOP)-EXP(-A*ZBOT))/.979
13130  RMASS=RMASS+RPROP(L)
13140  'PRINT  L , RPROP(L),FNTION18(V(L)+2,V16(L),V01(L)) , RMASS
13150  NEXT L
```

```
13160  RM=FNTION17(RMO,DOG)
13165  IF RM < 15 THEN RM = 15
13166  'PRINT RM
13167  NOLAY=INT(ZEFF/DZRT+1.001)
13168  FOR L=1 TO 9
13169  RPROP(L)=RPROP(L)/RMASS
13170  IF L<=NOLAY THEN 13172
13171  RPROP(L)=0
13172  NEXT L
13175  RETURN
13290  '*******************************************************************
13300  '        SOIL ROOT CONDUCTANCE AND LEAF WATER POTENTIAL
13301  '*******************************************************************
13302  IF DOG = 0 THEN 13890
13309  KSPEFF=0 :  PSIST=0  :  WMPSIS=0
13310  FOR L=1 TO 9
13320  RPROP(L)=RPROP(L)/RMASS
13330  KSP(L) = KSPO*(RPROP(L)*RM)^.5 * FNTION18(V(L)+1,V16(L),V01(L))/10
13340  KSPEFF = KSPEFF + KSP(L)
13350  WMPSIS = WMPSIS + KSP(L)*PSIS(L)
13360  'PRINT L,KSPEFF,KSP(L),PSIST,RPROP(L)
13370  NEXT L
13380  PSIST = WMPSIS / KSPEFF      ' WEIGHTED MEAN PSIS
13390  'PRINT PSIST
13395  GOSUB 5700
13400  LFLAG=0
13410  PSIL=PSIST+PTRANS/KSPEFF
13420  'PRINT USING "########";PSIL;PSIST
13440  PSIHI=0
13450  PSILO=-3500
13470  PSIT=(PSIHI+PSILO)/2
13480  FH=FNTION3(PSIT,PSIC)
13490  IF FH>1 THEN  FH=1
13500  IF FH < 0 THEN  FH=0
13510  IF PSIT>-3500 THEN 13540
13520  PRINT "ULTRA-STRESS, PSIL = -3000, ON DOY ";D
13530  STOP
13540  TRANS=FH*PTRANS
13550  PSIL=PSIST+TRANS/KSPEFF
13560  'PRINT PSIT,FH,TRANS,PSIL
13570  TEST=PSIL-PSIT
13580  IF TEST>5 THEN 13610
13590  IF TEST>-5 THEN 13700
13600  GOTO 13640
13610  REM PSIT TOO NEGATIVE
13620  PSILO=PSIT
13630  GOTO 13470
13640  REM PSIT TOO LITTLE NEGATIVE
13650  PSIHI=PSIT
13660  GOTO 13470
13680  '
13690  '*******************************************************************
13700  '                  EXTRACT WATER FROM EACH SOIL LAYER
13710  '*******************************************************************
13715  'PRINT USING "#####";PSIST; PSIL; :PRINT USING "####.#"; TRANS; PTRANS
```

```
13730  FOR L=1 TO 9
13740  TS(L)=-(PSIS(L)-PSIL)*KSP(L)
13750 'IF TS(L)>=0 THEN 13810
13760 'LFLAG=1
13770 'KSPEFF = KSPEFF - KSP(L)
13780 'WMPSIS = WMPSIS - KSP(L) * PSIS(L)
13790 'KSP(L)=0
13800 'TS(L)=0
13810  NEXT L
13820 'IF LFLAG=1 THEN 13400
13823  TRANS = 0
13824 TAW = 0
13825  WTEST = W(1)-TS(1)-SOILVAP
13826  IF WTEST < W16(1) THEN TS(1) = W(1) - W16(1) :W(1)=W16(1) :  GOTO 1382
13827  W(1) = WTEST
13828  V(1) = W(1) / DZRT    :  TRANS = TS(1)
13829  AW(1) = W(1) - W16(1) :  TAW = TAW + AW(1) : PAWL(1)=AW(1)/PAW(1)*100
13830  FOR L=2 TO 9
13840  WTEST=W(L)-TS(L)
13845  IF WTEST < W16(L) THEN TS(L) = W(L) - W16(L) :W(L)=W16(L)  : GOTO 1385
13847  W(L) = WTEST
13850  TRANS = TRANS+TS(L)
13860  V(L)=W(L)/DZRT
13862  AW(L)=W(L)-W16(L)
13864  TAW=TAW+AW(L)
13865 PAWL(L)=AW(L)/PAW(L)*100
13866  'PRINT L
13870  'PRINT USING  "#####"; L;W(L);V(L);TRANS*10;TS(L)*10;TAW
13880  NEXT L
13882  PPAW=TAW/TPAW*100
13885  'FH=TRANS/PTRANS
13890  RETURN
13899  '*******************************************************************
13900  '            DOY ON WHICH THE MONTHS END
13910  '*******************************************************************
13912  DAYS = 365
13914  IF YEAR MOD 4 = 0 THEN DAYS = 366
13922  MEND(1) = 31
13924  MEND(2) =  59
13926  IF DAYS = 366 THEN MEND(2)=60
13928  MENDG = MEND(2)
13940  FOR I=3 TO 12
13950  MEND(I)=MENDG + MONL(I)
13960  MENDG=MEND(I)
13970  NEXT I
13990  RETURN
13999  '*******************************************************************
14000  '              COEFFICIENTS SOIL WATER EXTRACTION CURVE
14001  '*******************************************************************
14010  DATA .00899,.00972,.00913,.00927,.00913,.00913,.00913,.00913,.00913
14020  FOR L=1 TO 9
14030  READ M(L)          : 'PRINT M(L)
14040  NEXT L
14050  DATA 9.56,13.65,14.51,14.84,10.45,12.20,12.20,12.2,12.2
14060  FOR L=1 TO 9
```

```
14070  READ PO(L)        : 'PRINT PO(L)
14080  NEXT L
14085  VINIT(L)=150
14090  RETURN
14091  '
14093  '*****************************************************************
14095  '          SUB TO RE-WRITE CARRY OVER FILE
14099  '*****************************************************************
14100  CLS:LOCATE 7,20:INPUT "ENTER NAME OF CARRY OVER FILE ",CO$
14110  OPEN "O",#1,CO$
14120  PRINT #1,N$:PRINT #1,W$:PRINT #1,C$
14130  PRINT #1,USING "####";D,DOG,PMONTH,PDAY,JP,STAGE,BEGIN,FINISH
14132  PRINT #1,USING "####";NPL,ENDEXT,ENDTIL,HUCO
14140  PRINT #1,USING "###.###";ZEFFO,DZRT,HT,LAI,HU,CU
14142  PRINT #1,USING "###.##";TTRANS,TPTRANS,WUSE,TSEVAP,DEEPERC,RT
14144  PRINT #1,USING "##.###";YO/1000,Y/1000,YEAR/1000
14150  FOR L=1 TO 9
14160  PRINT #1,USING "####";VINIT(L)
14170  NEXT L
14180  FOR L=1 TO 9
14190  PRINT #1,USING "#.####";M(L)
14200  NEXT L
14210  FOR L=1 TO 9
14220  PRINT #1,USING "###.##";PO(L)
14230  NEXT L
14235   CLOSE #1
14240  RETURN
14241 '
14244 '****************************************************************
14245 '            SUB TO ALTER INITIAL CONDITIONS
14247 '****************************************************************
14250 CLS:COLOR 11,0,0:LOCATE 2,20,1,4,6:PRINT "STATION";TAB(35);N$
14255 COLOR 11,12:LOCATE 3,20  :PRINT "N$=                    " :COLOR 11,0,0
14260 LOCATE 5,20  :PRINT "SOIL DESCRIPTION";TAB(40);W$
14265 COLOR 11,12:LOCATE 6,20  :PRINT "W$=                    " :COLOR 11,0,0
14270 LOCATE 8,20  :PRINT "WHEAT CULTIVAR";TAB(35);C$
14275 COLOR 11,12:LOCATE 9,20  :PRINT "C$=                    " :COLOR 11,0,0
14280 LOCATE 11,20  :PRINT "PLANTPOPULATION/ha";TAB(40);NPL
14285 COLOR 11,12:LOCATE 12,20  :PRINT "NPL=          ":COLOR 11,0,0
14290 LOCATE 14,20 :PRINT "STEM EXTENTION";TAB(35);ENDEXT
14295 COLOR 11,12:LOCATE 15,20 :PRINT "ENDEXT =             ":COLOR 11,0,0
14300 LOCATE 17,20 :PRINT "TILLERING";TAB(35);ENDTIL
14305 COLOR 11,12:LOCATE 18,20 :PRINT "ENDTIL =             ":COLOR 11,0,0
14310 LOCATE 20,20 :PRINT "SOIL LAYER DEPTH";TAB(40);DZRT
14315 COLOR 11,12:LOCATE 21,20 :PRINT "DZRT =              ":COLOR 11,0,0
14317 LOCATE 22,10:PRINT "MAKE CORRECTIONS IF INCORRECT ELSE PRESS CONT.(F5)";:S
TOP:CLS
14320  LOCATE 2,20 :COLOR 11,12:PRINT "MAX EFFECTIVE ROOTING DEPTH";TAB(55);ZEFF
O
14325  CLOSE #1
14330  LOCATE 5,20 :PRINT"CRIT MIN HEAT REQUIRED TO END OF TILLERING";TAB(65);HU
CO
14333 COLOR 11,12:LOCATE 8,20:PRINT"YO=      ";YO:COLOR 11,0
14334 COLOR 11,12:LOCATE 10,20:PRINT"Y      = ";Y:COLOR 11,0
14335 COLOR 11,0:LOCATE 6,20  :PRINT "HUCO=           " :COLOR 11,12
14337 LOCATE 11,10:COLOR 11,0:PRINT "MAKE CORRECTIONS IF INCORRECT ELSE PRESS CO
NT.(F5)";:PRINT :PRINT :STOP:CLS
14340 COLOR 11,12:LOCATE 1,2:PRINT"HT     = ";HT
14350 LOCATE 3,2:PRINT"LAI    = ";LAI
14360 LOCATE 5,2:PRINT"HU     = ";HU
14365 LOCATE 7,2:PRINT"CU     = ";CU
14370 LOCATE 9,2:PRINT"TTRANS= ";TTRANS
14380 LOCATE 11,2:PRINT"TPTRANS=";TPTRANS
14385 LOCATE 13,2:PRINT"WUSE  = ";WUSE
14390 LOCATE 15,2:PRINT"TSEVAP= ";TSEVAP
14400 LOCATE 17,2:PRINT"RT=      ";RT
14405 LOCATE 19,2:PRINT"DEEPERC=";DEEPERC:COLOR 11,0
14430 PRINT "MAKE CORRECTIONS IF INCORRECT ELSE PRESS CONT.(F5)";:STOP:CLS
14440 COLOR 11,12:FOR L=2 TO 18 STEP 2:LOCATE L,1:PRINT "VINIT(";L/2;")=
VINIT(L/2):NEXT L :COLOR 11,0:PRINT
14445 PRINT "CORRECT INITIAL SOIL MOISTURE IF INCORRECT ELSE PRESS CONT.(F5)
RINT:PRINT:STOP:CLS
14450 FOR L=1 TO 9 :W(L)=VINIT(L)*DZRT:V(L)=VINIT(L):NEXT L
14460 COLOR 11,12:FOR L=2 TO 18 STEP 2:LOCATE L,1:PRINT "M(";L/2;")=       ";
2):NEXT L :COLOR 11,0:PRINT
14465 PRINT "CORRECT IF INCORRECT ELSE PRESS CONT.(F5)";:PRINT:PRINT:STOP:C
14470 COLOR 11,12:FOR L=2 TO 18 STEP 2:LOCATE L,1:PRINT "PO(";L/2;")=
L/2):NEXT L :COLOR 11,0:PRINT
14475 PRINT "CORRECT IF INCORRECT ELSE PRESS CONT.(F5)";:PRINT:PRINT:STOP:CL
14490 COLOR 11,12:LOCATE 1,1:PRINT"PMONTH  = ";PMONTH;"   "
14495 COLOR 11,12:LOCATE 3,1:PRINT"PDAY    = ";PDAY;"   "
14500 COLOR 11,12:LOCATE 5,1:PRINT"STAGE   = ";STAGE;"   "
14510 COLOR 11,12:LOCATE 7,1:PRINT"JP      = ";JP;"   "
14520 COLOR 11,12:LOCATE 9,1:PRINT"DOY     = ";DOY;"   "
14530 COLOR 11,12:LOCATE 11,1:PRINT"DOG    = ";DOG;"   "
14540 COLOR 11,12:LOCATE 13,1:PRINT"BEGIN  = ";BEGIN;"   "
14545 COLOR 11,12:LOCATE 15,1:PRINT"FINISH = ";FINISH;"   "
14547 COLOR 11,12:LOCATE 17,1:PRINT"YEAR   = ";YEAR;"   ":COLOR 11,0
14550 PRINT "MAKE CORRECTIONS IF INCORRECT ELSE PRESS CONT.(F5)";:STOP:CLS
14555  GOSUB 14100
14560 RETURN
14599  '*****************************************************************
14600  ' READ RAIN, IRRIGATION, HAIL AND SPECIFIC DAYS TO RECORD
14601  '*****************************************************************
14602  OPEN "I", #4, "WCWIN"
14605  INPUT #4,NRAIN              'NUMBER OF DAYS ON WHICH IT RAINED
14610  FOR I = 1 TO NRAIN
14615  INPUT #4,  DOYRAIN(I),RAIN(I)
14620  NEXT I
14625  INPUT #4, NIR               'NUMBER OF DAYS ON WHICH IRRIGATED
14630  FOR I=1 TO NIR
14635  INPUT #4,  DOYIR(I),IRRIG(I)
14640  NEXT I
14645  INPUT #4, NHAIL             'NUMBER OF DAYS ON WHICH IT HAILED
14650  FOR I=1 TO NHAIL
14655  INPUT #4, DOYHAIL(I),HAILP(I)   ' PERCENTAGE HAIL
14660  NEXT I
14665  INPUT #4, NMEAS             'NUMBER OF DAYS ON WHICH TO TEST MODEL
14670  FOR I = 1 TO NMEAS
14675  INPUT #4, DOYMES(I )
14680  NEXT I
14685 'NEXT NM
14695  RETURN
14699  '*****************************************************************
14700  '       TO CREATE RAIN, HAIL AND IRRIGATION FILES
14701  '*****************************************************************
14710  OPEN "I", #4, "WCWIN"
14720  INPUT #4,COUNT
```

```
14730  FOR I = 1 TO COUNT
14740  INPUT #4, DOYRAIN,AMOUNT
14750  X(DOYRAIN,3) = AMOUNT
14760  NEXT I
14762  INPUT #4,COUNT
14764  FOR I = 1 TO COUNT
14766  INPUT #4, DOYIRR,AMOUNT
14768  X(DOYIRR,6) = AMOUNT
14770  NEXT I
14771  INPUT #4,COUNT
14772  FOR I = 1 TO COUNT
14773  INPUT #4, DOYHAIL,AMOUNT
14774  X(DOYHAIL,7) = AMOUNT
14775  NEXT I
14778  INPUT #4,COUNT
14780  FOR I = 1 TO COUNT
14782  INPUT #4, DOYMEAS
14783  X(DOYMEAS,8) = 22
14784  NEXT I
14790  RETURN
14999  '**************************************************************
15000  '                        THE FUNCTIONS
15010  '***************************************************************
15020  DEF FNSINK(FW)=(1-FW)*.06
15030  DEF FNLRED(NPL)=140      /NPL
15040  DEF FNDLENGTH(D)=12.15+1.93*COS((D+9)/365*2*3.14285)        'DAYLENGTH
15050  DEF FNMJD(D)= (30.84+12.65*COS((D+9)/365*2*3.14285))         'MJ m^-2 d^-1
15060  DEF FNDLYR(SO,KT,NMX)=SO*(.25+.75 * KT / NMX )               'MJ m^-2 d^-1
15070  DEF FNRAD(LAI)= 1 - EXP(-.7*LAI)
15080  DEF FNTION2(PSI,PSIC)=1-EXP(-8.000001E-03*(PSI-(PSIC-400))) 'FH
15090  DEF FNTION3(PSI,PSIC)=1/(1+EXP(2.000001E-03*( PSIC-PSI)))    'FW
15100  DEF FNTION4(PSI,PSIC)=1/(1+EXP(.004*(PSI-(PSIC-200))))
15110  DEF FNTION5(FG,FLE,PV)=FG*(1-FLE)*PV                         'Es
15120  DEF FNTION6(T,TO)=EXP(-.0048*(T-TO)^2)                        'Ft
15130  DEF FNTION8(T)=.402+.017*T-.00015*T^2                          's/(s+G)
15140  DEF FNTION9(LAI)=.186*LAI                                      'Fle
15150  DEF FNTION10(Z,H)=Z*1.35*H/2450/1000                           'Em
15160  DEF FNTION11(HU)=(-4170+17.1*HU-.02593*HU^2+17.09*10^(-6)*HU^3
       -4.0349*10^(-9)*HU^4)*10                                       'dG/dC
15170  DEF FNTION12(P)=.5*P                                           'SYNRESP
15180  DEF FNTION13(COO,TNITE,C)=COO*(.044+.0019*TNITE+.001*TNITE^2)*C 'MAINRESP
15190  DEF FNTION14(HU,NPL) = .85/(1+482*EXP(-.012*HU))*NPL*10^(-4)     'LAP
15200  DEF FNTION15(POL,ML,VL)=-EXP(POL*EXP(-ML*VL))                  'PSIS
15210  DEF FNTION16(ML,PL,POL)= (-1/ML*LOG(PL/POL))
15220  DEF FNTION17(RMO,DOG)=RMO* 1/(1+EXP(-.06*(DOG-50)))            'REL ROOTMASS
15230  DEF FNTION18(V,V16,V01)= (LOG(V/V16))/LOG(V01/V16)
15240  DEF FNTION19(DOG,FW)=((-2.09*10^(-4)*DOG^3+8.914999E-02*DOG^2-.8819*DOG+1
2.749)/1000)*FW                                                          'HT
15250  DEF FNTION20(Q10,DELHU,FLGRO)=Q10 * DELHU * FLGRO                  'DELLAP
15260  DEF FNTION21(VIDEF) = EXP(-.03*VIDEF)                          'Fg
15262  DEF FNTION22(CLAY)=.1387+.00416*CLAY                           ' V10
15270  RETURN
16000  PRINT "END"
16020  CLOSE
16030  END
```

APPENDIX V - LISTING: REGISTER

```
10 REM PROGRAM TO WRITE EACH FARMER'S WATER USE RECORD ON PAPER (NAME REGISTER)
20 OPTION BASE 0
30 DIM AKKWATER(300),WV(300),D(300),AMOUNT(300),FWDO(300),WDIEP(300)
50 INPUT"FILE NAME", A$
60 OPEN "I",#1,A$
70 INPUT #1,TITLE$,DAYS
80 IF MID$(TITLE$,4,1)="1" THEN GROND$="FYNSAND"
90 IF MID$(TITLE$,4,1)="2" THEN GROND$="LEEMSAND"
100 IF MID$(TITLE$,4,1)="4" THEN GROND$="SANDKLEILEEM"
110 IF MID$(TITLE$,4,1)="3" THEN GROND$="SANDLEEM"
120 PRINT TITLE$
130 FOR N=1 TO DAYS
140 INPUT #1,D(N),WV(N),WDIEP(N)
150 PRINT    D(N),WV(N),WDIEP(N)
160 NEXT N
170 INPUT"STARTING AND FINAL DATE OF WEEK ( COMMAS BETWEEN TWO DATES)",DAT$,DATU
M$
180 INPUT"HOW MANY FARMERS",FARMS
190 FOR FARMERS=1 TO FARMS
200 INPUT "FARMER NAME AND BLOCK",N$
210 INPUT"MAXIMUM ROOTING DEPTH (m)";WORTEL
220 INPUT"WATER EXTRACTION ON THE LAST DAY OF PREVIOUS WEEK (mm)";AKKWATER(DAYS-
7)
230 INPUT"ANY CHANCE OF STREMMING (1 OR 0)";ANSWER
240 IF ANSWER=1 THEN 260
250 GOTO 330
260 INPUT"DAY OF WEEK on which stremming should occur",DDD
270 N=DAYS-6+DDD
280 REM
290 FOR N=DAYS-6+DDD TO DAYS+1
300 FWDO(N)=FWDO(N-1)+50
310 IF FWDO(N)>100 THEN FWDO(N)=100
320 NEXT N
330 INPUT"NUMBER OF RAIN AND IRRIGATION DAYS",ANTWOORD
340 IF ANTWOORD=>1 THEN 361
350 GOSUB 490
360 GOTO 470
361 FOR QQQQ=1 TO ANTWOORD
370 INPUT"DAY OF WEEK",DAG
380 N=DAYS-7+DAG
390 INPUT"AMOUNT(MM)",AMOUNT(N)
391 NEXT QQQQ
400 GOSUB 490
410 FOR N=DAYS-6 TO DAYS
420 AMOUNT(N)=0
430 AKKWATER(N)=0
440 FWDO(N)=0
450 FW=0
460 NEXT N
470 NEXT FARMERS
480 END
490 REM SUBROUTINE CALCULATES AND PRINTS WATER USE
500 REM
510 REM
520 REM
530 FOR N=DAYS-6 TO DAYS
540 AKKWATER(N)=AKKWATER(N-1)+WV(N)
550 IF AMOUNT(N) >0 THEN AKKWATER(N)=AKKWATER(N-1)+WV(N)-AMOUNT(N)
560 IF AMOUNT(N)>0 THEN  FW=1
570 IF FW=1 THEN FWDO(N)=0
580          IF AKKWATER(N)<0 THEN AKKWATER(N)=0
590 IF WDIEP(N)>WORTEL THEN WDIEP(N)=WORTEL
600 NEXT N
610 PRINT
620 PRINT
630 PRINT
640 LPRINT"*****************************************************************
***********"
650 LPRINT"WATERVERBRUIKSADVIESNOTA"
660 LPRINT"------------------------"
670 LPRINT
680 LPRINT N$
690 LPRINT
700 LPRINT DAT$;" - ";DATUM$
710 LPRINT
720 LPRINT "GRONDTIPE:";GROND$
730 LPRINT
740 LPRINT"BERAAMDE WORTELDIEPTE OP DIE LAASTE DAG VAN DIE WEEK:",WDIEP(DAYS)*10
00;"mm"
750 LPRINT
760 LPRINT"KALENDERDAG     WATERVERBRUIK   AKUMULATIEWE     BESPROEIING       PER
SENTASIE
770 LPRINT"                                WATERVERBRUIK                      STR
EMMING"
780 LPRINT"                     mm/d            mm                mm
 %"
790 LPRINT"-----------------------------------------------------------------
---------"
800 REM
810 FOR N=DAYS-6 TO DAYS
820 LPRINT USING "###.#            ";D(N),WV(N),AKKWATER(N),AMOUNT(N),FWDO(N)
830 NEXT N
840 LPRINT"-----------------------------------------------------------------
---------"
850 LPRINT"*****************************************************************
***********"
860 RETURN
```

```
5     ' ---------------------------------------------------------------------
10    ' PROGRAMME TO WRITE VALUES OF TE (CALCULATED FROM HOURLY VALUES TO
20    ' DISK.   :LATEST MODIFICATION OF PROGRAMME ON 86-07-07:
30    ' PROGRAM NAAM:TEREF84.BAS
45    ' ---------------------------------------------------------------------
46      OPTION BASE 1
50      DIM W(32,25),S1(32,25),T(32,25),RH(32,25),S(32,25),L(32),TMAX(366)
60      DIM Y(30),D(366),TEM(366),DOY(32),KONK(32)
70      DIM RADD(366),TEMPD(366),RHD(366),WINDSD(366),RAIND(366),TMIN(366)
75      DIM TEMP(31,24),WINDS(31,24),RAIN(31,24),X(30),RAD(31,24),TER(366)
76    ' ---------------------------------------------------------------------
80      GOSUB 100                                   'PARAMETERS
82      GOSUB 2030                                  'LEES DATALEER
84      GOSUB 5000                                  'BEREKENINGS
86      GOSUB 5500                                  'SKRYF RESULTATE
88      RUN
89    '
90    ' ---------------------------------------------------------------------
95    '                       SUBROUTINE PARAMETERS
99    ' ---------------------------------------------------------------------
100     BO=8 : TT=0 : GO=-1 : HEMX=20 : FW=1 : MXRAT=20 : CLS : PLDAT=183
110     RV =12.85    ' THE MINIMUM HYDRAULIC RESISTANCE OF THE VEGETATION s/m
180     RETURN
200   '
2020  ' ---------------------------------------------------------------------
2030  '                       INLEES VAN WEERELEMENTE
2040  ' ---------------------------------------------------------------------
2050    INPUT "AFKOTING VAN MAAND          (eg.    AUG       )":FILE$
2055    FILE$="A:"+FILE$+"-84-2.UUR"
2060    INPUT "NUMBER OF DAYS IN DATA FILE":EIND
2070    OPEN "I",#1,FILE$
2080    FOR I = 1 TO EIND
2085    TMX=0:TMN=40
2090    FOR H=1 TO 24
2100    INPUT #1,A$
2110    D=VAL(MID$(A$,3,3)):IF I=1 THEN DI=D
2111    IF I=EIND THEN DF=D
2112    DOY(I)=D
2120    RAD(I,H)  =VAL (MID$(A$,8,7))
2130    TEMP(I,H) =VAL(MID$(A$,15,6))
2140    RH(I,H)   =VAL(MID$(A$,21,6))
2150    WINDS(I,H)=VAL(MID$(A$,27,6))
2160    RAIN(I,H) =VAL(MID$(A$,39,5))
2170    GOSUB 7000
2175    IF KONK(I) = 1 THEN 2220
2180    RADD(D)=RADD(D)+RAD(I,H)
2190    IF TEMP(I,H)<TMN THEN TMN=TEMP(I,H)
2191    IF TEMP(I,H)>TMX THEN TMX=TEMP(I,H)
2200    RHD(D)=RHD(D)+RH(I,H)
2201    RAIND(D)=RAIND(D)+RAIN(I,H)
2210    WINDSD(D)=WINDSD(D)+WINDS(I,H)
2220    NEXT   H : IF KONK(I) = 1 THEN 2240
2221    TMAX(D)=TMX:TMIN(D)=TMN  :RADD(D)=RADD(D)*3600*10^(-6)
2222    WINDSD(D)=WINDSD(D)/24
2230    PRINT USING "####.####":D,H,TMAX(D),TMIN(D),RAIND(D),RADD(D)
```

```
2240   NEXT I
2400   RETURN
2410 '
2450 ' ------------------------------------------------------------------------
5000 '            VERBAND TUSSEN SVI(PYR.),SVD(NIPP) & Rn-G
5001 ' ------------------------------------------------------------------------
5010   FOR I=1 TO EIND
5015   IF KONK(I) = 1 THEN 5390
5020   FOR H=7 TO 18
5030   IF RAD(I,H)<0 THEN RAD(I,H)=0
5040   RAD(I,H)=((RAD(I,H)*.515-60 ))
5050   IF RAD(I,H)<0 THEN RAD(I,H)=0
5055   DPLD=DOY(I)-PLDAT+1 : IF DPLD < 0 THEN DPLD=0
5080   HOOG =-2.09*10^(-4)*(DPLD^3)+.089148*(DPLD^2)-.881999*(DPLD)+12.74
5081   HOOG = HOOG/1000
5100   IF HOOG >.8 THEN HOOG=.8
5110   IF HOOG <.05  THEN HOOG=.05
5130   D1=.63*HOOG : D1R = .63*.05
5140   ZO=.13*HOOG : ZOR = .13*.05
5230   E1=6.11*EXP(5347*(1/273-1/(273+TEMP(I,H))))
5240   E2=RH(I,H)*E1/100
5250   DELTA=E1/(273+TEMP(I,H))^2*(6790.5-5.02808*(273+TEMP(I,H))+4916.8*10^(-.0
304*(273+TEMP(I,H)))*(273+TEMP(I,H))^2+1.74209*10^5*10^(-1302.88/(273+TEMP(I,H))
))
5260     E3=E1-E2
5270   IF WINDS(I,H)=0 THEN WINDS(I,H)=.1
5280   RA=(LOG((2-D1)/ZO)^2)/(.41^2 * WINDS(I,H))
5285   RAR=(LOG((2-D1R)/ZOR)^2)/(.41^2 * WINDS(I,H))
5290   KONA=1/RA
5295   KONAR=1/RAR
5300   GAMA=.66*(1+KONA/.03)
5305   GAMAR=.66*(1+KONAR/.03)
5310 ' KONDUKTANSIE VAN GEWASOPPERVLAKTE WORD BERAAM OP 0.03 m/s
5320 ' 1/RC=1/20=0.03(3)
5330   LEP=(RAD(I,H)*DELTA+1.2*1010*E3*KONA)/(DELTA+GAMA)
5335   LEPR=(RAD(I,H)*DELTA+1.2*1010*E3*KONAR)/(DELTA+GAMAR)
5340   LEP=LEP*3600/(2454*10^3)
5345   LEPR=LEPR*3600/(2454*10^3)
5350   D=DOY(I)
5360   TER(D) = TER(D)+LEPR
5380  TEM(D)=TEM(D)+LEP
5382 NEXT H
5385  PRINT WINDSD(D),RADD(D),TER(D),HOOG
5370   NEXT I
5400   RETURN
5410 '
5499 ' ------------------------------------------------------------------------
5500 '            SUBROUTINE OM DAAGLIKSE DATA OP DISKET TE STOOR
5510 ' ------------------------------------------------------------------------
5900  UIT$="1984FRF"
6010  OPEN "A",#4,UIT$     'VIR EERSTE LOPIE VERVANG "A" MET "O"
6015  FOR D=DI TO DF
6020   PRINT #4,USING"####.##";D;TMAX(D);TMIN(D);RAIND(D);RADD(D); TER(D);TEM(D)
6040  NEXT D
6050  RETURN
6052 '
6055 ' ------------------------------------------------------------------------
6058 '            SUBROUTINE OM VERMISTE DATA TE VERVANG
6060 ' ------------------------------------------------------------------------
7000   IF KONK(I) = 1 THEN  8010
7002   IF H > 7 AND H < 18 THEN 7080
7009   IF RAD(I,H)<-99  AND H=1 THEN RAD(I,H)=0
7010   IF RAD(I,H)<-99 THEN RAD(I,H)=RAD(I,H-1)
7020   IF TEMP(I,H)<-99  AND H=1 THEN TEMP(I,H)=-99
7030   IF TEMP(I,H)<-99 THEN TEMP(I,H)=TEMP(I,H-1)
7040   IF WINDS(I,H)<-99  AND H=1 THEN WINDS(I,H)=1
7050   IF WINDS(I,H)<-99 THEN WINDS(I,H)=WINDS(I,H-1)
7060   IF RAIN(I,H)<-99  AND H=1 THEN RAIN(I,H)=0
7070   IF RAIN(I,H)<-99 THEN RAIN(I,H)=RAIN(I,H-1) : GOTO 8010
7080   IF RAD(I,H)   <-99 THEN RADD(D)  =-99.9 : KONK(I) = 1
7090   IF RAIN(I,H)  <-99 THEN RAIND(D)  =-99.9 : KONK(I) = 1
8000   IF WINDS(I,H)<-99 THEN WINDSD(D)=-99.9 : KONK(I) = 1
8010   RETURN
```

APPENDIX VII – LISTING: PRINT DAILY, MONTHLY SUMMARY

```
10    REM                                                                    BRUCE-86
20    REM ********************************************************************
30    REM *                                                                  *
40    REM * PROGRAM ; "BRUCE";AGROMETEOROLOGY MET-SITE 2 - Experimental plot  *
50    REM *                  :Prints daily & monthly summaries of met data   *
60    REM *                                                                  *
70    REM *  bruce kelbe : 04/3/1985 : 10/01/1986                            *
80    REM *                                                                  *
90    REM ********************************************************************
100   REM
110   REM
120        OPTION BASE 1
130        CLEAR
140        DIM A$(80),X(16),MON(33,16),JULIAN(13),MONTH$(12),Z(2,16),SX(5,24),SN(
5,24),SS(5,24)
150        DATA   0,     1,     2,   0.05,  2.5E06
160        READ FIN,RECORD,HEIGHT,  CROP,    LAMBDA
170        ZO = .13*CROP
180        DATA "          "," NNE  "," ENE  "," ESE  "," SSE  "," SSW  "
190        DATA "  WSW  "," WNW  "," NNW  "
200        FOR I=1 TO 9
210          READ DIR$(I)
220        NEXT I
230        DATA 0,31,59,90,120,151,181,212,243,273,304,334,365
240        INPUT "YEAR";YEAR
250        INPUT "LAST LYSIMETER WEIGHT mV";WEIGHT
260        YR=YEAR
270        FOR I=1 TO 13
280          READ JULIAN(I)
290          IF INT(YR/4)=YR/4 AND I>2 THEN JULIAN(I)=JULIAN(I)+1
300        NEXT I
310        DATA " JANUARY "," FEBRUARY","  MARCH  ","  APRIL  ","   MAY   ","   J
UNE  ", "  JULY  "," AUGUST  ","SEPTEMBER"," OCTOBER "," NOVEMBER"," DECEMBER"
320        FOR I=1 TO 12
330          READ MONTH$(I)
340        NEXT I
350        CLOSE
360        INPUT "FILE REQUIRED (eg. ''B:MARCH.DAT )";FILE$
370   OPEN "I",#1,FILE$
380       WHT=WEIGHT
390       LPRINT CHR$(27)+CHR$(76)+CHR$(48)+CHR$(49)+CHR$(48)
400       RECORD=1 : TIME=100 : IRRIG=0
410     IF RECORD=1 AND EOF(1)=0 THEN INPUT #1,A$ ELSE IF EOF(1) GOTO 2140
420       RECORD=1
430       IF MID$(A$,1,2)="09" THEN STOP
440       IF MID$(A$,4,4)="0249" THEN LPRINT USING "###.##";VAL(MID$(A$,23,6));:G
OTO 410
450       P=LEN(A$)
460       FOR I=1 TO P STEP 10
470         K=VAL(MID$(A$,I,2))
480         X(K)=VAL(MID$(A$,I+2,6))
490       NEXT I
500       IF P<78  GOTO 550
510     INPUT #1,A$
520       IF MID$(A$,4,4)="0249" THEN LPRINT USING "###.##";VAL(MID$(A$,23,6));:
GOTO 510
530       IF MID$(A$,1,2)="09" GOTO 450
540       RECORD=2
550       NUM=K
560 REM BRANCH TO CORRECT TABLE  >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
570      IF X(1)=2 GOTO 960 ELSE IF X(1)=3 GOTO 1330
580 REM .........................................................TABLE #1
590         IF x(3)=100 OR TIME=100 THEN GOTO 1570
```

```
600       LPRINT
610       IF X(3)<> TIME THEN GOSUB 2620
620       LPRINT USING "###";TIME/100;
630       TIME=TIME+100
640       IF NUM=11 THEN X(16)=0 ELSE IF NUM>11 THEN X(16)=X(12)
650       FOR I=4 TO 12
660         IF I=4 THEN X(I)=X(I)*1000/360
670         IF I=6 THEN GOTO 760
680         IF I=7 THEN X(I)=X(I)-10
690         IF I=10 THEN GOSUB 2000
700         IF I=12 THEN GOSUB 2100
720     IF I=11 THEN LPRINT USING "#####.#";X(I);ELSE IF I=12 AND X(I)=0 THEN LP
RINT "        ";ELSE LPRINT USING "####.##";X(I);
730         IF X(I)<-99 THEN X(I)=-99.99 : GOTO 760
740         Z(1,I)=Z(1,I)+X(I)
750         Z(2,I)=Z(2,I)+1
760       NEXT I
770       WEIGHT=X(11)
780       Z(1,12)=(WHT-WEIGHT)
790       Z(1,12)=Z(1,12)*.152
800       GOSUB 1840
810       LPRINT USING "####.##";EP;
820       IF EP<.01 THEN EP=.01
830       IF ABS(X(12)/EP)>999 THEN LPRINT "      .  "; ELSE LPRINT USING "####.##
";X(12)/EP;
840       IF X(16)=0 THEN GOTO 870
850       LPRINT USING "####.#";X(16);
860       LPRINT "*";
870       EP=-99.99
880       IRRIG=IRRIG+X(16) : X(16)=0
890       N=INT(X(3)/100)
900       IF X(4)>-1 THEN SX(1,N)=SX(1,N)+X(4) : SN(1,N)=SN(1,N)+1 : SS(1,N)=SS(
1,N)+X(4)^2
910       IF X(5)>-99 THEN SX(2,N)=SX(2,N)+X(5) : SN(2,N)=SN(2,N)+1 : SS(2,N)=SS
(2,N)+X(5)^2
920       IF X(6)>0 THEN SX(5,N)=SX(5,N)+X(6) : SN(5,N)=SN(5,N)+1 : SS(5,N)=SS(5
,N)+X(6)^2
930       IF X(7)>0 THEN SX(3,N)=SX(3,N)+X(7) : SN(3,N)=SN(3,N)+1 : SS(3,N)=SS(3
,N)+X(7)^2
940       IF X(10)>0 THEN SX(4,N)=SX(4,N)+X(10) : SN(4,N)=SN(4,N)+1 : SS(4,N)=SS
(4,N)+X(10)^2
950       GOTO 410
960  REM ..............................................................TABLE #2
970       LPRINT
980       IF DOY<241 THEN X(4)=X(4)*20/25
990       LPRINT CHR$(27)+CHR$(33)
1000       LPRINT "Ave ";
1010         IF Z(2,4)<22 THEN LPRINT "         "; ELSE LPRINT USING "###.##";Z(1,4
)/Z(2,4);
1020       FOR I=5 TO 10
1030         IF I=6 THEN GOTO 1050
1040         IF Z(2,I)<22 THEN LPRINT "         "; ELSE LPRINT USING "####.##";Z(1
,I)/Z(2,I);
1050       NEXT I
1060 LPRINT
1070 LPRINT "Total";
1080       LPRINT TAB(46) USING "#####.##";(WEIGHT-WHT);
1090       LPRINT USING "###.##";Z(1,12);
1100       IF EVAP>.1 THEN LPRINT USING "####.##";EVAP;ELSE LPRINT "         ";
1110       IF EVAP>.1 THEN LPRINT USING "####.##";Z(1,12)/EVAP;ELSE LPRINT "
 ";
1120       LPRINT USING "###.#";X(4)
1130       WHT=WEIGHT
1140       IF IRRIG>0 THEN IR$="yes" ELSE IR$="no"
1150       LPRINT
1160       LPRINT CHR$(27)+CHR$(34)
1170       LPRINT "A-Pan        (mm)";TAB(20);"  Irrigation (";IR$;")";
1180       IF Z(2,5)<12 THEN MON(DATE,2)=-99.99 ELSE MON(DATE,2)=Z(1,5)/Z(2,5)
1190       IF Z(2,7)<12 THEN MON(DATE,3)=-99.99 ELSE MON(DATE,3)=Z(1,7)/Z(2,7)
1200       IF Z(2,8)<12 THEN MON(DATE,4)=-99.99 ELSE MON(DATE,4)=Z(1,8)/Z(2,8)
1210       IF Z(2,9)<12 THEN MON(DATE,5)=-99.99 ELSE MON(DATE,5)=Z(1,9)/Z(2,9)
1220       IF Z(2,10)<12 THEN MON(DATE,6)=-99.99 ELSE MON(DATE,6)=Z(1,10)/Z(2,10
)
1230       IF X(4)<0 THEN MON(DATE,8)=-99.99 ELSE MON(DATE,8)=X(4)*20/25
1240       MON(DATE,9)=Z(1,12)
1250       MON(DATE,10)=EVAP
1260       FOR I=1 TO 2
1270         FOR J=1 TO 16
1280           Z(I,J)=0
1290         NEXT J
1300       NEXT I
1310       IRRIG=0 : X(12)=0
1320       GOTO 410
1330  REM .............................................................TABLE #3
1340       IF X(2)<-10 THEN MON(DATE,1)=-99.99 ELSE MON(DATE,1)=X(2)*86.4
1350       LPRINT
1360       LPRINT
1370       LPRINT
1380       LPRINT "WIND-DIRECTION - RELATIVE FREQUENCY(%) IN 45 DEGREE SECTORS"
1390       LPRINT
1400       LPRINT "degrees     0  ->  45 ->   90  ->  135 ->  180 ->  225 ->  270
 ->  315  -> 360"
1410       LPRINT "frequency ";
1420       S=0
1430       FOR I=3 TO 10
1440         IF X(I)<0 THEN X(I)=-.9999
1450         IF X(I)<S THEN GOTO 1480
1460         N=I
1470         S=X(I)
1480         LPRINT USING "#####.##";X(I)*100;
1490       NEXT I
1500       TIME=100
1510       LPRINT
1520       LPRINT
1530       MON(DATE,7)=(N-1)
1540       IF MON(DATE,7)<0 THEN LPRINT "Highest frequency ->  -99.99 " ELSE LPR
INT "Highest frequency -> ";DIR$(N-1)
1550       IF FIN=1 THEN GOSUB 2140
1560       GOTO 410
1570   REM  ......................................SUBROUTINE TO PRINT HEADINGS
1580   LPRINT CHR$(12);
1590   LPRINT CHR$(27)+CHR$(69)
1600   LPRINT TAB(65);"D ";X(2)
1610   LPRINT CHR$(14);CHR$(27)+CHR$(78);CHR$(27)+CHR$(33)
1620   LPRINT "UNIVERSITY";CHR$(27)+CHR$(81);"  of the";CHR$(27)+CHR$(78);" ORAN
GE FREE STATE"
1630   LPRINT "   Department  Agrometeorology "
1640   LPRINT CHR$(27)+CHR$(80);"              Experimental Plot"
1650   LPRINT CHR$(15);CHR$(27)+CHR$(69);CHR$(27)+CHR$(34)
1660   LPRINT
1670   YR=YEAR-1900
1680   FOR I=1 TO 13
1690     IF X(2)<= JULIAN(I) GOTO 1710
1700   NEXT I
1710   IF X(2)=JULIAN(I) THEN FIN=1
1720   I=I-1
1730   MONTH=I
```

```
1740   DATE=X(2)-JULIAN(I)
1750   IF DATE=1 THEN FIN=0
1760   LPRINT "     Date :";DATE;"/";MONTH$(I);"/";YEAR,TAB(60);"DOY :";X(2)
1770   LPRINT CHR$(27)+CHR$(33)
1780   LPRINT "Time  Radtn  Temp   R.H.  Calibrations   Wind  Lysmtr   Ea      Ep
   Ea/   RAIN"
1790   LPRINT "        W/m";CHR$(27);"&";CHR$(81);CHR$(27);"$";SPC(4);CHR$(27);"&"
;CHR$(79);CHR$(27);"$";"C      %     T( C)     RH(%)    m/s      mV      mm/hr   mm/hr
/Ep"
1800   LPRINT CHR$(27)+CHR$(34)
1810   LPRINT TAB(46) USING "#####.#";WEIGHT;
1820   EVAP=0
1830   GOTO 600
1840 REM ...........................................POTENTIAL EVAPOTRANSPORATION
1850   IF X(4)<-99 OR X(5)<-99 OR X(7)<-99 OR X(10)<-99 THEN RETURN
1860   TEMP=X(5)+273.15
1870   CONST=.4019914 + .017251 * X(5) - .0001485 * X(5) * X(5)
1880   IF X(4)<148 THEN ER=0 ELSE ER=CONST * ((X(4)-148)/.88)/LAMBDA *3600
1890   RH=(LOG((HEIGHT-.64 * CROP)/ZO))^2/(.41 *.41 * X(10))
1900   EVS=EXP(52.5763-6790.499/TEMP-5.02808*LOG(TEMP))/(.000462*TEMP)
1910   VAP=(1-X(7)/100)*EVS/1000
1920   EV=(1-CONST)*VAP/RH *3600
1930   EP=ER+EV
1940   EVAP=EVAP+EP
1950   RETURN
1960 REM...................................................RADIATION
1970   X(I)=X(I)*1000/360
1990   RETURN
2000 REM ....................................................WIND CORRECTIONS
2010 '
2020 '
2030 '
2040 '
2080   RETURN
2090 REM ...............................................LYSIMETER CORRECTIONS
2100   IF WEIGHT < 0 THEN WEIGHT = X(I-1)
2110   X(12)=(WEIGHT-X(11))
2120   X(12)=X(12)*.152
2130  RETURN
2140 REM ...................................................MONTHLY SUMMARY
2150   GOSUB 2670 : 'PRINT HOURLY MEANS
2160   INPUT "FILE FOR STORING MONTHLY SUMMARY(eg.B:JAN.MON)";FILE$
2170   OPEN "O",#2,FILE$
2180   LPRINT CHR$(12);
2190   LPRINT TAB(65);"C- ";MONTH
2200   LPRINT CHR$(14);CHR$(27)+CHR$(78);CHR$(27)+CHR$(33)
2210   LPRINT "UNIVERSITY";CHR$(27)+CHR$(81);"  of the";CHR$(27)+CHR$(78);" ORAN
GE FREE STATE"
2220   LPRINT "   Department Agrometeorology"
2230   LPRINT CHR$(27)+CHR$(80);"           Experimental Plot"
2240   LPRINT CHR$(15);CHR$(27)+CHR$(69);CHR$(27)+CHR$(34)
2250   LPRINT
2260   LPRINT TAB(20);MONTH$(MONTH);"-";YEAR;
2270   LPRINT
2280   LPRINT CHR$(27)+CHR$(33)
2290   LPRINT " Day  Radtn   Temp   R.H.  Calibrations    Wind      Rain   Total
  Total"
2300   LPRINT "       total   mean   mean                 speed angel           E
a     Ep"
2310   LPRINT "      MJ/m";CHR$(27)+CHR$(115)+CHR$(49);CHR$(27)+CHR$(81);"2";SPC
(6);"O";CHR$(27)+CHR$(115)+CHR$(48);CHR$(27)+CHR$(69);"C      %       C    %RH
  m/s  deg       mm   mm/day"
2320  LPRINT CHR$(27)+CHR$(34)
2330   FOR I=1 TO 10
2340      MON(32,I)=0
2350      MON(33,I)=0
2360    NEXT I
2370    FOR I=1 TO DATE
2380     LPRINT USING "####";I;
2390      FOR J=1 TO 10
2400        IF J=7 THEN LPRINT DIR$(MON(I,J)); ELSE IF J=8 AND MON(I,J)=0 THEN LP
RINT "      "; ELSE IF MON(I,J)<-90 THEN LPRINT "          "; ELSE LPRINT USING "#
###.##";MON(I,J);
2410        IF MON(I,J)>-99 THEN MON(32,J)=MON(32,J)+MON(I,J)
2420        IF MON(I,J)>-99 THEN MON(33,J)=MON(33,J)+1
2430        PRINT #2,MON(I,J)
2440        MON(I,J)=0
2450      NEXT J
2460     LPRINT
2470    NEXT I
2480    MON(33,8)=1
2490    FIN=0
2500   LPRINT CHR$(27)+CHR$(33)
2510   LPRINT "MEAN";
2520    FOR J=1 TO 10
2530      IF J=7 THEN LPRINT "        "; ELSE LPRINT USING "####.##";MON(32,J)/MON
(33,J);
2540      PRINT #2,MON(32,J)/MON(33,J)
2550    NEXT J
2560    FOR I=1 TO 17
2570     LPRINT
2580    NEXT I
2590    LPRINT CHR$(27)+CHR$(34)
2600    CLOSE
2610    END
2620 REM .................................................Missing times
2630        FOR I=TIME+100 TO X(3)-100 STEP 100
2640          LPRINT USING "###";I/100
2650        NEXT I
2660        RETURN
2670 REM ...................................................Hourly means
2680        LPRINT CHR$(12)
2690        LPRINT
2700        LPRINT TAB(10);FILE$ : LPRINT TAB(10);"MEAN HOURLY VALUES"
2710        LPRINT "     Time      Rad      Temp      Rel Hum  Wind speed  Lys"
2720        FOR I=1 TO 24
2730          LPRINT USING "######.##";I;SX(1,I)/SN(1,I);SX(2,I)/SN(2,I);SX(3,I)
/SN(3,I);SX(4,I)/SN(4,I);SX(5,I)/SN(5,I)
2740        NEXT I
2750        LPRINT : LPRINT : LPRINT TAB(10);"STANDARD DEVIATION" : LPRINT
2760        'STANDARD DEVIATION
2770        FOR I=1 TO 24
2780          FOR J=1 TO 5
2790            SS(J,I)=SQR((SS(J,I)-(SX(J,I)^2/SN(J,I)))/(SN(J,I)-1))
2800            IF SN(J,I)<2 THEN SS(J,I)=-999.99
2810          NEXT J
2820          LPRINT USING "#######.##";I;SS(1,I);SS(2,I);SS(3,I);SS(4,I);SS(5,I
)
2830        NEXT I
2840        RETURN
```

```
10      '                                                                    EXPLOT84
20      '*********************************************************************
30      '*                                                                   *
40      '* PROGRAM ; TO TRANSFORM AUTOMATIC WEATHER DATA WITH CORRECTION TO   *
50      '*           HOURLY (File-2) AND DAILY (File-3) DATA FILES           *
60      '*                                                                   *
70      '*  bruce kelbe : 24/6/1986  Converted from "BRUCE-84"               *
80      '*                                                                   *
90      '*********************************************************************
100     '
110     '
120      OPTION BASE 1
130      CLEAR
140      DIM A$(80),X(16),MON(33,16),JULIAN(13),MONTH$(12),Z(2,16),SX(5,24)
150      DIM SN(5,24),SS(5,24)
160      DATA   0, 1, 2, 0.05, 2.5E06, 0.20 , 0
170      READ FIN, RECORD, HEIGHT, CROP, LAMBDA , CRP    , EP1
180      ZO = .13*CROP : Z1 = .13*CRP
185      MIN=99.99 : WMIN=99.99 : MAX=-99.99 : WMAX=-99.99 : MIS=0
190      DATA "        "," NNE ","  ENE  "," ESE  "," SSE  "," SSW  "
200      DATA " WSW  ","  WNW  "," NNW  "
210      FOR I=1 TO 9
220        READ DIR$(I)
230      NEXT I
240      DATA 0,31,59,90,120,151,181,212,243,273,304,334,365
250      INPUT "YEAR";YEAR
260      INPUT "LAST LYSIMETER WEIGHT mV";WEIGHT
270      YR=YEAR
280      FOR I=1 TO 13
290        READ JULIAN(I)
300        IF INT(YR/4)=YR/4 AND I>2 THEN JULIAN(I)=JULIAN(I)+1
310      NEXT I
320      DATA " JANUARY "," FEBRUARY","  MARCH  ","  APRIL  ","   MAY   ","   J
UNE  ", "   JULY  "," AUGUST  ","SEPTEMBER"," OCTOBER "," NOVEMBER"," DECEMBER"
330      FOR I=1 TO 12
340        READ MONTH$(I)
350      NEXT I
360      CLOSE
370      INPUT "SOURCE FILE REQUIRED           (eg. C:MON-YR.EXP )";FILE$
380      OPEN "I",#1,FILE$
410      INPUT "OUTPUT HOURLY FILE REQUIRED (eg. A:MON-YR-#.UUR)";FILE$
420      OPEN "O",#2,FILE$
430      INPUT "OUTPUT DAILY FILE REQUIRED  (eg. B:MON-YR-#.DAG)";FILE$
440      OPEN "O",#3,FILE$
441      INPUT "ENTER NAME OUTPUT WIND FILE (eg. B:MON-YR-#.WND)";FILE$
442      OPEN "O",#4,FILE$
450      WHT=WEIGHT
460      RECORD=1 : IRRIG=0
470      IF RECORD=1 AND EOF(1)=0 THEN INPUT #1,A$ ELSE IF EOF(1) GOTO 1760
480      RECORD=1
490      IF MID$(A$,1,2)="09" THEN STOP
500      IF MID$(A$,4,4)="0249" THEN GOTO 1580
510      P=LEN(A$)
520      FOR I=1 TO P STEP 10
530       K=VAL(MID$(A$,I,2))
540       X(K)=VAL(MID$(A$,I+2,6))
550      NEXT I
560      IF P<78  GOTO 610
570      INPUT #1,A$
580      IF MID$(A$,4,4)="0249" THEN GOTO 1610
590      IF MID$(A$,1,2)="09" GOTO 510
600      RECORD=2
610      NUM=K
620      BRANCH TO CORRECT TABLE  >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
```

```
630       IF X(1)=2 GOTO 1040 ELSE IF X(1)=3 GOTO 1300
640     ' .............................................................TABLE #1
650       IF X(3)=100 THEN GOTO 1460
660       DOY = X(2)
665        PRINT #2, "84";
670       PRINT #2, USING "###"; X(2); ;PRINT X(2),
671       PRINT #2, USING "##"; X(3)/100;;PRINT X(3)
680       IF NUM=11 THEN X(16)=0 ELSE IF NUM>11 THEN X(16)=X(12)
690       FOR I=4 TO 12
700         IF I=4 THEN GOSUB 2080
710         IF I=5  AND X(I)<-90 THEN GOTO 720
720         IF I=6  THEN GOTO 880
770         IF I=7  THEN GOSUB 1800
780         IF I=10 THEN GOSUB 1930
790         IF I=11 THEN GOSUB 1980
800         IF I=12 AND WEIGHT<0 THEN WEIGHT = X(I-1)
810         IF I=12 THEN X(I)=(WEIGHT-X(I-1))*.32222
820         IF X(I)<-99 THEN X(I)=-99.99
830         IF I=6 OR I=8 OR I=9 OR I=12 THEN GOTO 850
840         IF X(I)<-99 THEN MIS = MIS + 1
850         IF X(I)<-99 OR X(I)=-99.99 THEN GOTO 880
852         IF I=10 AND X(10)>WMAX THEN WMAX=X(10)
854         IF I=10 AND X(10)<WMIN THEN WMIN=X(10)
856         IF I=5  AND X(5) >MAX  THEN MAX=X(5)
858         IF I=5  AND X(5) <MIN  THEN MIN=X(5)
860         Z(1,I)=Z(1,I)+X(I)
870         Z(2,I)=Z(2,I)+1
880       NEXT I
890     PRINT #2,USING "####.##";X(4);;PRINT #2,USING "###.##";X(5);X(7);X(10);
900       Z(1,12)=(WHT-WEIGHT)*.322
910       WEIGHT=X(11)
930       PRINT #2,USING "####.#";WEIGHT;
940       IF RAIN=0 THEN PRINT #2,"   .0" ELSE PRINT #2,USING "###.#";RAIN : RAI
N=0
970       N=INT(X(3)/100)
980       IF X(4)>-1  THEN SX(1,N)=SX(1,N)+X(4)  : SN(1,N)=SN(1,N)+1  : SS(1,N)=SS
(1,N)+X(4)^2
990       IF X(5)>-99 THEN SX(2,N)=SX(2,N)+X(5)  : SN(2,N)=SN(2,N)+1  : SS(2,N)=SS
(2,N)+X(5)^2
1000        IF X(6)>0   THEN SX(5,N)=SX(5,N)+X(6)  : SN(5,N)=SN(5,N)+1  : SS(5,N)=S
S(5,N)+X(6)^2
1010        IF X(7)>0   THEN SX(3,N)=SX(3,N)+X(7)  : SN(3,N)=SN(3,N)+1  : SS(3,N)=S
S(3,N)+X(7)^2
1020        IF X(10)>0  THEN SX(4,N)=SX(4,N)+X(10)  : SN(4,N)=SN(4,N)+1  : SS(4,N)=
SS(4,N)+X(10)^2
1030        GOTO 470
```

```
1040    ' ..............................................................TABLE #2
1050      PRINT #3,"84";
1060      IF DOY<241 THEN X(4)=X(4)*20/25
1070      IF Z(2,7)  = 0 THEN Z(2,7)  = -99.99
1080      IF Z(2,10) = 0 THEN Z(2,10) = -99.99
1090      IF Z(2,4)  = 0 THEN Z(2,4)  = -99.99
1100      IF Z(2,5)  = 0 THEN Z(2,5)  = -99.99
1105      IF X(4)<0 THEN X(4)=-99.9
1110      IF X(5)   <-99 THEN X(5)=-99900!:X(6)=-99900!
1120      PRINT #3, USING "###"    ;DOY;                               '==========3
1140      PRINT #3, USING "####"   ;MIS;                               '==========3
1150      PRINT #3, USING "####.##";Z(1,4)/Z(2,4);                   '==========3
1160      PRINT #3, USING "###.##" ;MAX,MIN;Z(1,5)/Z(2,5);Z(1,7)/Z(2,7);
1170      PRINT #3, USING "###.##" ;Z(1,10)/Z(2,10);:WINDY=Z(1,10)/Z(2,10)
1175      PRINT #3, USING "###.#"  ;X(4);                              '==========3 .
1180      PRINT #3, USING "####.#" ;X(5)/1000,X(6)/1000;
1190      PRINT #3, USING "#####.#";(WEIGHT-WHT)
1205      MIN=99.99 : MAX=-99.99 : MIS=0
1210      EP1 = 0
1220      WHT=WEIGHT
1230      FOR I=1 TO 2
1240       FOR J=1 TO 16
1250          Z(I,J)=0
1260       NEXT J
1270     NEXT I
1280     X(12)=0
1290     GOTO 470


1300    ' ..............................................................TABLE #3
1310     S=0 : PRINT #4,"84";
1320     PRINT #4, USING "###" ;DOY;
1330     PRINT #4, USING "###.##";WINDY;
1340     PRINT #4, USING "###.##";WMAX;WMIN;
1345     WMIN=99.99 : WMAX=-99.99 : MIS=0
1350     FOR I=3 TO 10
1360       IF X(I)<0 THEN X(I)=-.9999
1370       IF X(I)<S THEN GOTO 1400
1380       N=I
1390       S=X(I)
1400       PRINT #4, USING "##.###";X(I);
1410     NEXT I
1420     IF X(2)<0 THEN PRINT #4,"-99.99"ELSE PRINT #4,USING "###.##";X(2)*86.4
1430     MON(DATE,7)=(N-1)
1440     IF FIN=1 THEN GOSUB 1760
1450     GOTO 470
```

```
1460   ' ......................................
1470    YR=YEAR-1900
1480    FOR I=1 TO 13
1490      IF X(2)<= JULIAN(I) GOTO 1510
1500    NEXT I
1510    IF X(2)=JULIAN(I)  THEN FIN=1
1520    I=I-1
1530    MONTH=I
1540    DATE=X(2)-JULIAN(I)
1550    IF DATE=1 THEN FIN=0
1560    EVAP=0
1570    GOTO 665


1580  ' ...........................................................RAINFALL
1590    RAIN = VAL(MID$(A$,23,6))*20/25
1600    GOTO 470


1610  ' ...........................................................RAINFALL
1620   RAIN = VAL(MID$(A$,23,6))*20/25
1630   GOTO 570


1760  ' .....................................................END
1780   CLOSE
1790   END
```

```
1800   ' .........................................Relative humidity from T,Tw
1810    IF X(7)<-99 THEN RETURN ELSE IF X(2)>19 GOTO 1890
1820    TD=X(5)+273.15
1830    TW=X(7)+273.15
1840    ES=EXP(52.5763 - 6790.499/TD - 5.02808 * LOG(TD))/TD/.000462
1850    EA=EXP(52.5763 - 6790.499/TW - 5.02808 * LOG(TW))/TW/.000462
1860    EA=EA-(1.2*1004*1000)/LAMBDA*(TD-TW)
1870    X(7)=EA/ES*100
1880    RETURN


1890    IF X(2)=20 AND X(3)<1000 GOTO 1820
1900    IF X(2)<26 THEN X(7)=X(7)-29.29*2
1910    X(7)=X(7) - 10
1920    RETURN


1930   ' ..................................................Wind corrections
1940    IF X(10)<0 OR X(2)>240 THEN RETURN
1950    IF X(2)>90  THEN X(10)=(X(10)-.447)*6+.447
1960    IF X(2)<90 THEN X(10)=X(10)*6+.447
1970    RETURN


1980   ' ................................................LYSIMETER CORRECTIONS
1990    IF X(2)>256 AND X(2)<283 THEN GOTO 2070
2000    IF X(2)=303 AND X(3)<10 THEN X(11)=X(11)+524
2010    IF X(2)<27 OR X(2)>40 THEN RETURN
2020    X(11)=X(6)*1000-1500
2030    IF X(11)>1000 THEN X(11)=X(11)/1000
2040    RETURN


2050    IF X(2)=282 AND X(3)>1400 THEN RETURN
2060    X(11)=X(6)-1000
2070    RETURN


2080   ' ....................................................RADIATION
2090    X(4)=X(4)*1000/360
2100    RETURN
```

APPENDIX IX

COMPARISONS OF WEATHER VARIABLES AND TESTS ON EQUIPMENT

Relationship between measurements on West Campus and "Die Bult"

As explained, it was necessary to determine the relationship between values of certain weather elements measured at "Die Bult" and corresponding measurements made at West Campus in order to replace missing data. Results of regressions involving radiation temperature, relative humidity and wind are given in Table IX.1. The high correlation coefficients and low mean absolute differences mean that the regression equations should provide reasonably reliable estimates.

It was deemed necessary to check whether the data logger in the automatic weather station was providing reliable records of lysimeter changes in mass. This was done by comparing values registered on the CR21 with those measured on the Keithly digital volt meter. The results of the tests are given in Table IX.2. Once again the high SI and low MAD indicate that the CR21 was functioning accurately for the measurements made over both daily and hourly intervals.

TABLE IX.1 - Statistical analysis of relationship between West Campus and Die Bult measured values of hourly mean (W/m^2) and daily ($MJ/(m^2d)$) radiant flux density, hourly temperature, hourly relative humidity and hourly mean wind speed.

Y - West Campus X - Die Bult	RAD W/m^2	AUG85 RAD MJ/d	OCT85 RAD MJ/d	OCT85 TEMP °C	OCT85 RH %	SEPT85 WIND m/s
n	57	23	25	28	28	29
SLOPE	1,06	0,72	1,07	1,03	1,08	1,23
INTERCEPT	37,34	6,68	2,12	-0,10	-15,24	1,36
r	0,99	0,96	0,99	0,98	0,98	0,88
MEAN OF MEASURED VALUES	437,77	15,75	18,7	19,60	59,46	1,83
MAD	61,44	2,30	3,38	0,55	10,68	1,77
SIMULATION INDEX	0,98	0,59	0,90	0,98	0,88	0,59

TABLE IX.2 - Statistical analysis of agreement between lysimeter total evaporation, E, registered on Keithly and CR21 recorders on a daily or an hourly basis.

Y X	E Keithly E CR21 mm/d	 mm/h
n	9	68
SLOPE	0,86	0,91
INTERCEPT (mm/-)	0,70	0,07
r	0,98	0,94
MEAN OF MEASURED VALUES	5,31	0,71
MAD (mm/-)	0,20	0,07
SIMULATION INDEX	0,99	0,97

The slope in the daily values is seriously affected by a simple outlier. On grounds of the evidence in this table it was concluded that the lysimeter connected to the CR21 was functioning satisfactorily.

APPENDIX X

RESULTS FROM THE COOPERATIVE EXPERIMENTS OF 1982 AND 1983

This appendix reflects the data collected in the cooperative experiments during 1982 and 1983.

INVENTORY

TABLE X.1 - Day of the year on which irrigation took place on four sites in the Vaalhaarts/Hartswater trials during 1982.

	A		B		C		D	
	FARM	UOFS	FARM	UOFS	FARM	UOFS	FARM	UOFS
	176	176	167	167	155	155	174	174
	223	223	203	203	196	196	217	217
	237	237	222	222	217		225	225
	251	215	235	235		225	242	242
	266	266	249	249	230		251	251
	279	279	260	260		235	258	
	293	293	271	271	244	244	265	265
	306	306	278	278		258	279	279
			287	287	266	266		
			303	303	279	279		
FREQUENCY	8	8	10	10	7	8	8	7

TABLE X.2a - A-pan evaporation, rainfall, irrigation and measured and calculated water use and pan factors for Site A during 1982.

PERIOD	A-PAN EVAP.	RAINFALL	IRRIGATION	WATER USE MEAS	WATER USE CALC	PAN FACTORS MEAS	PAN FACTORS CALC	PAN FACTORS CALC/MEAS
	(mm)	(mm)	(mm)	(mm)	(mm)			
222-228	43		62 (223)	13	18	0,3	0.4	1,3
229-235	49			20	9	0,4	0,2	0,5
236-242	49		62 (237)	20	34	0,4	0,7	1,8
243-249	49			12	43	0,3	0,9	3,0
250-256	60		62 (251)	21	55	0,4	0,9	2,3
257-263	59			47	52	0,8	0,9	1,1
264-270	56		62 (266)	26	59	0,5	1,0	2,0
271-277	72			44	68	0,6	1,0	1,7
178-284	61	11 4	62 (278)	30	64	0,5	1,0	2,0
285-291	31	5 11 3		31	45	1,0	1,5	1,5
292-298	58	5	62 (293)	47	63	0,8	1,1	1,4
299-305	49	6 16 1		25	62	0,5	1,3	2,6
TOTAL	636	62	372	336	572			

TABLE X.2b - A-pan evaporation, rainfall, irrigation and measured and calculated water use and pan factors for Site B, during 1982.

PERIOD	A-PAN EVAP.	RAINFALL	IRRIGATION	WATER USE MEAS	WATER USE CALC	PAN FACTORS MEAS	PAN FACTORS CALC	PAN FACTORS CALC/MEAS
	(mm)	(mm)	(mm)	(mm)	(mm)			
222-228	43		75 (222)	-	30		0,7	
229-235	49		75 (235)	-	35		0,7	
				*				
236-242	49			51**	43	1,0	0,9	0,9
243-249	49		75 (249)	-	48		1,0	
250-256	60			65	56	1,1	0,9	0,8
257-263	59		75 (260)	53	53	0,9	0,9	1,0
264-270	56			33**	66	0,6	1,2	2,0
271-277	72		75 (271)	72	68	1,0	1,0	1,0
278-284	61	11	75 (278)	68	64	1,1	1,0	0,9
285-291	31	5 11 3	75 (287)	48	45	1,6	1,5	0,9
292-298	58	5 9 5		46	63	0,8	1,1	1,4
299-305	49	6 16 1	75 (303)	69	62	1,4	1,3	0,9
TOTAL	636	72	675	421	411			

** Ignore   * Estimate

Table X.3 - Leaf area indices measured and calculated during 1982.

DATE	DOY	LEAF AREA INDEX SITE A CAL	LEAF AREA INDEX SITE A MEAS	LEAF AREA INDEX SITE B CAL	LEAF AREA INDEX SITE B MEAS
08/10	222	0,8	0,8	2,0	2,0
08/17	229	0,9	1,7	2,8	3,1
08/24	236	1,6	2,6	3,8	3,8
08/31	243	3,3	4,1	5,1	4,9
09/07	250	4,4	4,4	6,3	6,1
09/14	257	6,1	8,1	7,8	5,8
09/21	264	7,9	5,3	9,8	7,2
09/28	271	9,7	4,7	8,7	5,6
10/05	278	8,1	2	7,3	2,1
10/12	285	6,9	3,5	6,3	2,7
10/19	292	5,6	2,2	5,1	2,2
10/26	299	4,3	3,6	3,8	3,8

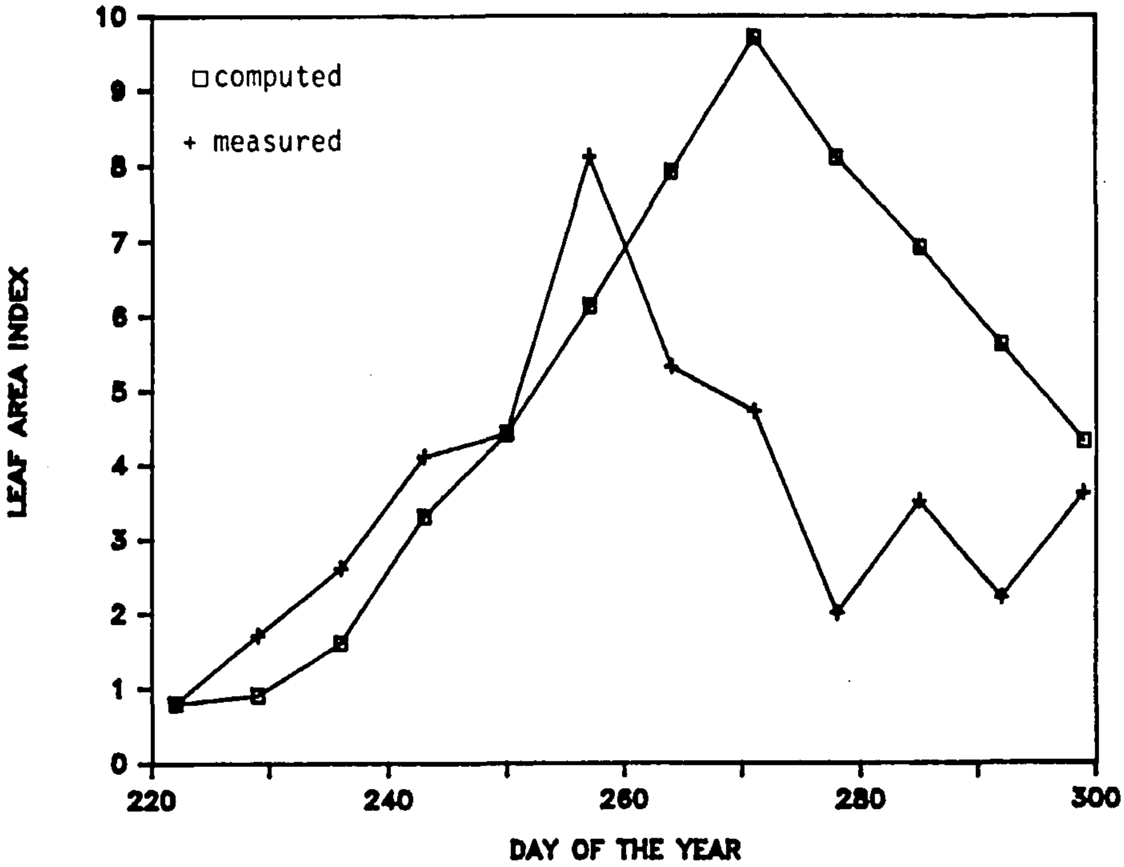


FIG. X.4a - Measured and calculated leaf area indices at site A during 1982.

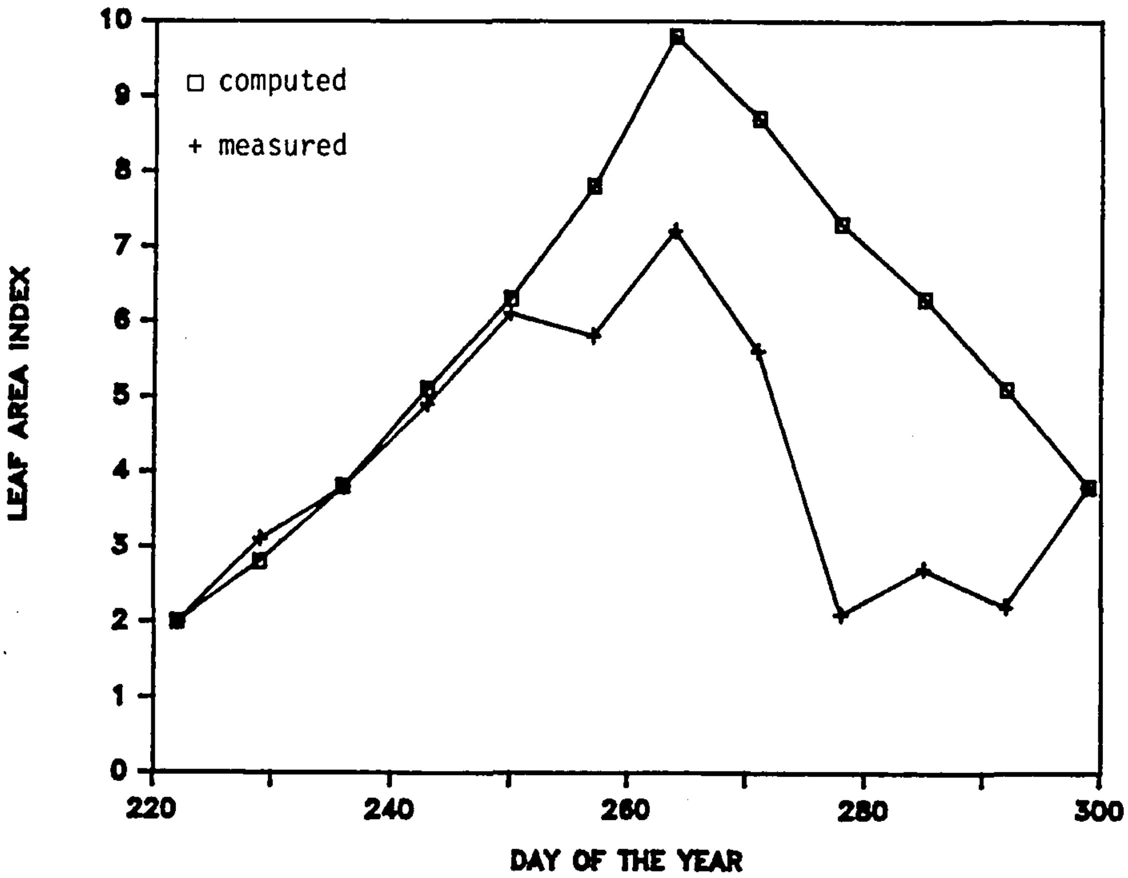


FIG. X.4b - Measured and calculated leaf area indices at site B during 1982

Table X.5a - Pre-dawn and noon leaf water potential (bar) at site A, 1982.

DATE	DOY	LEAF WATER POTENTIAL			
		PRE-DAWN		NOON	
		CALC	MEAS	CALC	MEAS
08/10	222	0,1	4,0	9,8	18,4
08/17	229	0,1	2,6	10,9	15,8
08/24	236	1,1	4,7	10,9	14,9
08/31	243	2,6	4,0	16,2	13,9
09/07	250	0,4	3,8	12,2	16,9
09/14	257	6,8	11,4	6,9	15,7
09/21	264	0,5	1,6	16,3	17,0
09/28	271	1,1	2,3	19,2	19,5
10/05	278	6,7	6,4	25,3	19,1
10/12	285	1,6	4,0	10,8	16,0
10/19	292	1,3	4,0	13,1	12,1
10/26	299	1,6	4,1	18,1	18,0

TABLE X.5b - Pre-dawn and noon leaf water potential at site B, 1982.

DATE	DOY	LEAF WATER POTENTIAL			
		PRE-DAWN		NOON	
		CALC	MEAS	CALC	MEAS
08/10	222	0,1	2,0	10,0	14,9
08/17	229	0,4	4,4	11,5	14,2
08/24	236	1,2	6,2	11,1	13,5
08/31	243	3,0	7,5	17,4	15,0
09/07	250	0,4	2,0	12,3	18,1
09/14	257	7,0	5,3	7,1	17,3
09/21	264	0,5	0,6	16,5	-
09/28	271	1,1	3,1	19,2	19,1
10/05	278	7,7	3,9	25,2	16,8
10/12	285	1,6	3,0	10,7	18,9
10/19	292	1,3	7,3	13,1	16,5
10/26	299	1,5	3,9	18,1	-

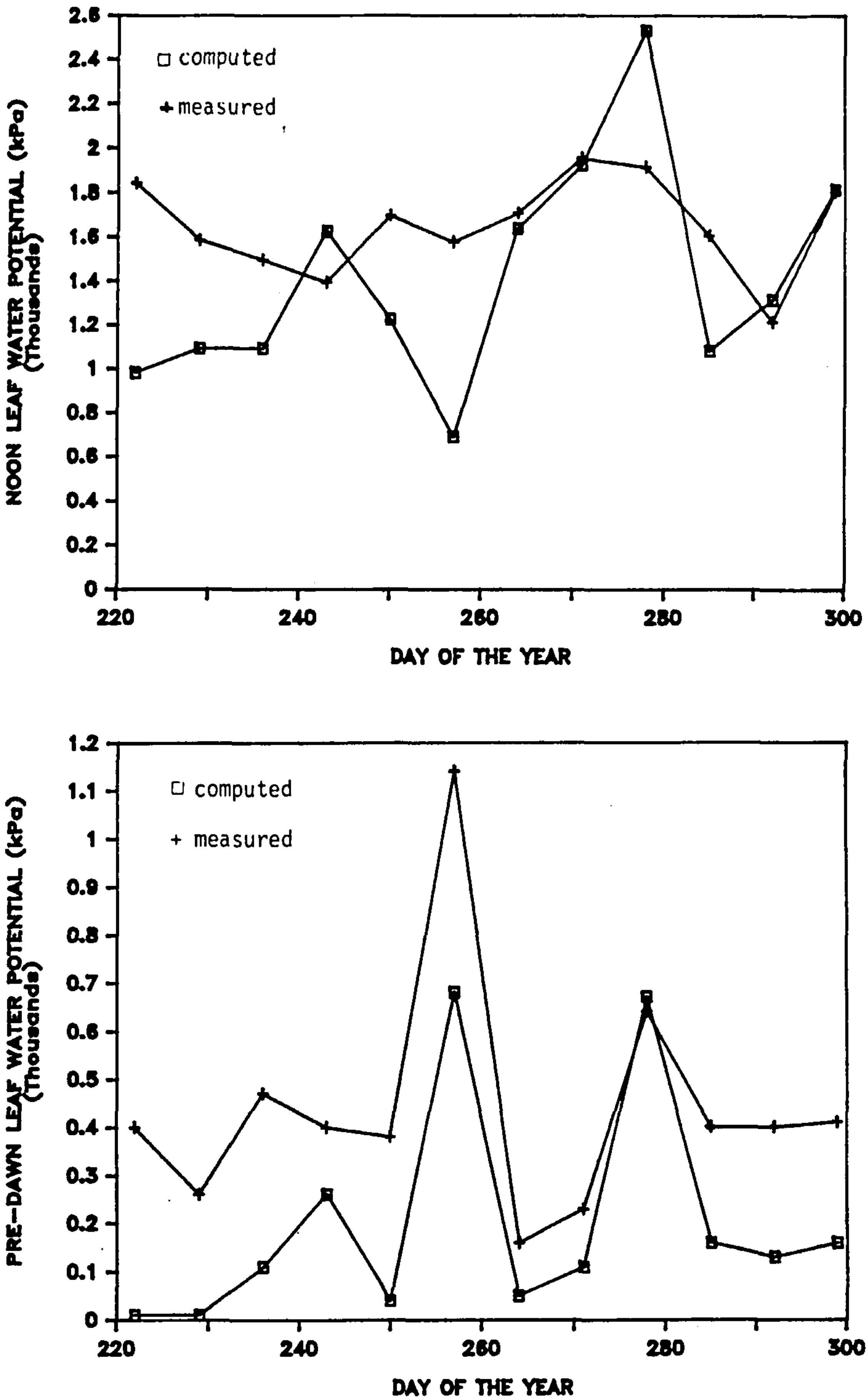


FIG. X.6 - Noon and pre-dawn leaf water potential at Site A, 1982

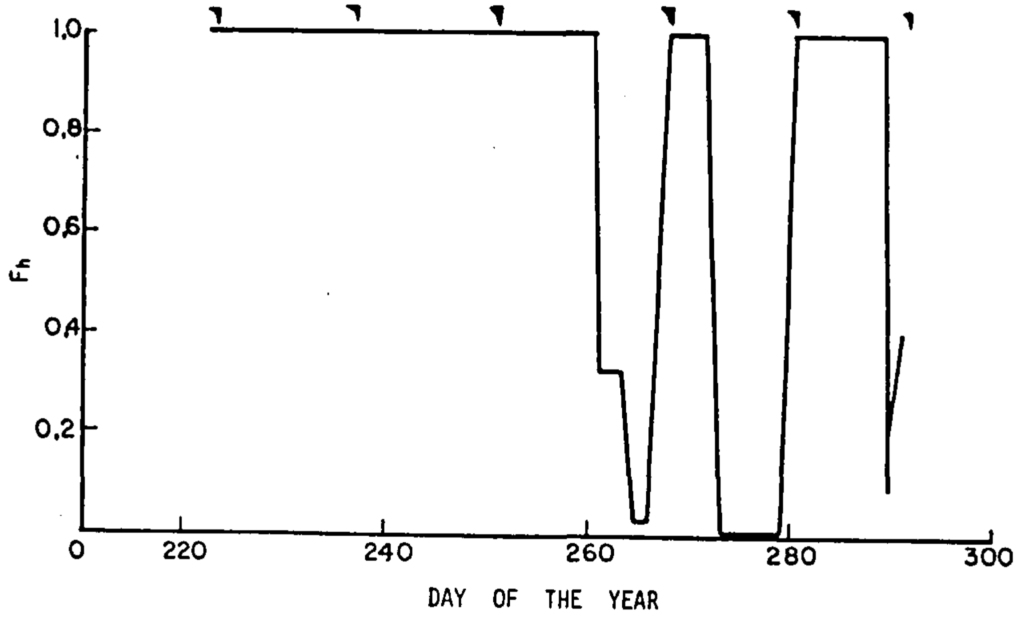


FIG. X.7a - Scenario of the Hydraulic scheduling factor, Fh, on Site A during 1982.

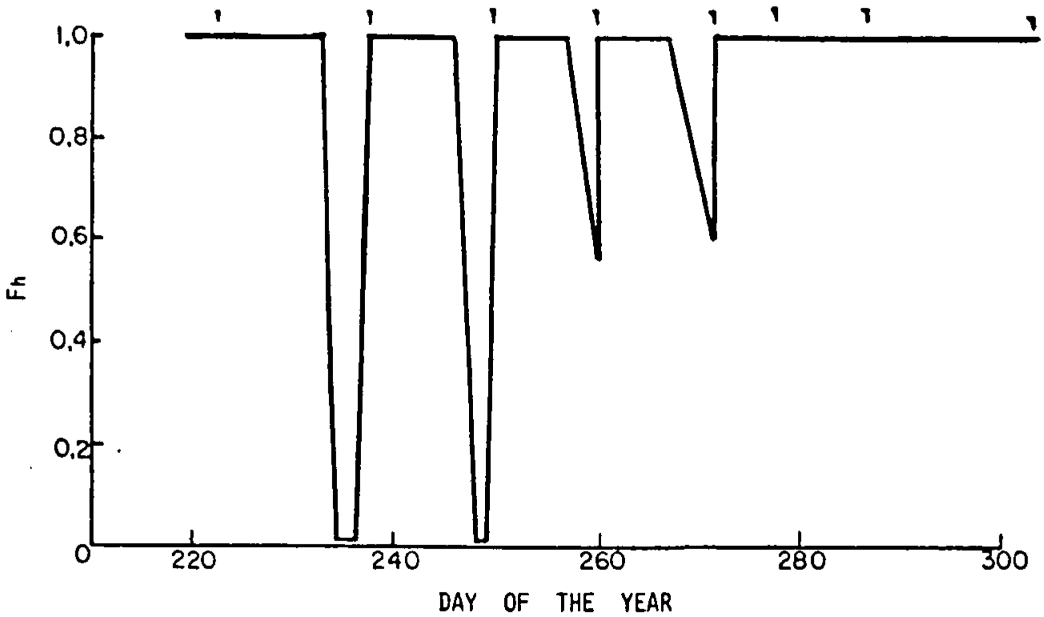


FIG. X.7b - Scenario of the hydraulic scheduling factor, Fh, on Site B, 1982.

TABLE X.8a - Day of the year (DOY) on which rainfall occurred and the amounts at the six Sites investigated.

SITE	DAY OF THE YEAR	RAIN (mm)
A	168	11
	205	25
	263	9
	282	32
	291	13
B	168	11
	205	25
	263	9
	280	32
	291	13
C	168	11
	205	25
	263	7
	282	38
	291	12
D	168	11
	205	25
	263	7
	282	38
	291	12
E	168	20
	205	24
	281	20
F	148	20
	206	40
	282	9
	283	6
	288	10
	311	13

TABLE X.8b - Day of the year on which irrigation took place on six sites in the Vaalharts/Hartswater and Bultfontein trails during 1983.

A		B		C		D		E		F	
FARM	UOFS	FARM	UOFS	FARM	UOFS	FARM	UOFS	FARM	UOFS	FARM	UOFS
167	167	164	164	165	165	157	157	165	165	140	140
214	214	192	192	185	-	187	187	201	201	147	147
235	-	221	221	222	222	221	221	224	224	196	196
250	250	-	250	264	264	238	-	242	-	224	224
264	265	257	-	-	300	248	248	259	259	238	238
278	278	263	-			279	279	276	276	250	250
299	299	-	265			300	300			264	264
		278	278							278	278
		300	300							292	292
										306	306
7	6	7	7	4	4	7	6	6	5	10	10

TABLE X.9 - A-pan evaporation, rainfall, irrigation and measured and simulated water use and pan factors for Site A during 1983.

PERIOD	A-PAN	RAINFALL	IRRI	WATER USE MEAS	WATER USE SIM	PAN FACTORS MEAS	PAN FACTORS SIM	PAN FACTORS SIM/MEAS
	(mm)	(mm)	(mm)	(mm)	(mm)			
207-216	68*			25,0	14,7	0,37	0,27	0,73
217-221	-		214	-	-	-		
222-229	52,5			24,2	12,6	0,46	0,24	0,52
230-235	38,5			10,4	17,3	0,27	0,45	1,67
236-242	50,0			10,4	33,9	0,21	0,68	3,24
243-249	63,0			14,6	45,7	0,23	0,73	1,60
250-256	46,0		250	33,2	50,1	0,72	1,09	1,51
257-263	57,9	9 (263)		32,2	46,2	0,56	0,80	1,43
264-270	44,1		265	39,8	48,8	0,90	1,12	1,24
271-277	50,5			80,7	55,9	1,60	1,11	0,69
278-291	84,0	32 (282)	278	80,0	107,2		1,28	
292-298	54,0	13 (291)			5,2		0,10	
TOTAL	608,5	54		350,5	437,6			

* Evaporation on two of the days was estimated.

TABLE X.10a - A-pan evaporation, rainfall, irrigation and measured and simulated water use and pan factors for Site B during 1983.

PERIOD	A-PAN	RAIN-FALL	IRRI	WATER USE MEAS	WATER USE SIM	PAN FACTORS MEAS	PAN FACTORS SIM	PAN FACTORS SIM/MEAS
	(mm)	(mm)	(mm)	(mm)	(mm)			
207-216	68,0*			27,9	10,8	0,41	0,16	0,39
217-221	-		221					
222-229	52,5			44,5	15,3	0,85	0,29	0,34
230-235	38,5			16,7	14,0	0,43	0,36	0,84
236-242	50,0			15,8	34,4	0,37	0,69	1,86
243-249	63,0			14,9	16,9	0,27	0,27	1,00
250-256	46,0		250	49,1	56,2	1,07	1,22	1,14
257-263	57,9	9 (263)		28,9	51,6	0,50	0,89	1,78
264-270	44,1		265		42,9		0,97	
271-277	50,5				56,8		1,12	
278-291	84,0	32 (280)	278		123,0		1,46	
292-298	54,0	13 (291)			47,1		0,87	
TOTAL	608,5	54		197,8	468,5			

TABLE X.10b - A-pan evaporation, rainfall, irrigation and measured and simulated water use and pan factors for Site F during 1983.

PERIOD	A-PAN	RAIN-FALL	IRRI	WATER USE MEAS	WATER USE SIM	PAN FACTORS MEAS	PAN FACTORS SIM	PAN FACTORS SIM/MEAS
	(mm)	(mm)	(mm)	(mm)	(mm)			
195-201	31,9		196	49,8	17,2	1,56	0,54	0,35
202-216	61,4*	40 (206)		33,0	41,3	0,54	0,67	1,25
217-222	23,7			13,9	16,4	0,59	0,27	0,46
223-229	34,5		224	48,4	27,4	1,40	0,79	0,56
230-235	31,6				25,8		0,82	
236-244	55,0*		238		24,3		0,44	
245-250	59,0		250		0,8		0,01	
251-264	96,3		264		2,7		0,03	
265-270	50,7				4,0		0,08	
271-280	108,3		278		16,6		0,15	
281-292	88,3	16 (282)	292		16,3		0,18	
293-299	60,3	10 (288)			30,5		0,51	
300-311	95,4	13 (311)	306		44,5		0,47	
TOTAL	851,7	79			252,8			

* Evaporation on two of the days was estimated.

TABLE X. 11a - Crop morphological and physiological data and soil water contents measured at Site A, 1983.

DOY	CROP HEIGHT	GROWTH STAGE	ROOT DEPTH	LAI		LEAF WATER POTENTIAL				MEASURED LAYER θg		
				MEAS	CALC	MEASURED 06H00	MEASURED 12H00	CALCULATED 06H00	CALCULATED 12H00	,0-,3	,3-,6	,6-,9
	(m)		(m)			(bar)	(bar)	(bar)	(bar)	(%)	(%)	(%)
186	0	Tillering	0,2		0			3	6,6	7,6	10,5	11,8
193	0		0,2		0,2	3,4	19,6	0,1	6,2	7,5	10,3	11,8
200	0,1		0,3	0,2	0,2	1,9	16,6	0,3	5,6	6,3	10	11,3
207	0,1		0,4	0,3	0,3	2,2	8,4	0,2	2,7	11,5	9,9	11,2
216	0,1		0,5	0,7	0,4	1,4	17,3	0,4	8,1	8	10	11,6
221	0,1		0,6	1	0,8	1,2	17	0,1	6,9	10,6	11,4	12,7
229	0,2		0,8	1,3	1,8	3,1	18,1	0,1	8,1	7,1	10,5	11,8
235	0,2		0,8	1,5	2,5	1,3	15	0,2	9,3	6,1	9,6	11,6
242	0,3		0,9	1,9	3,5	2,3	21,3	1,7	12,8	5,1	8,9	11,1
249	0,3	Heading	1,0	2,2	5,1	9,6	22,9	4,1	16,7	4,8	8,5	11,1
256	0,4		1,0	1,8	6,7	1	24,2	1,1	10,9	9,2	10,8	11,8
263	0,4	Flowering	1,0	2,4	7,9	5,5	24,5	1,5	11,5	6,1	8,6	10,9
270	0,7		1,0	2,8	7	4,4	22,6	3,9	13,1	8,5	10,5	11,5
277	0,7		1,0	1,1	5,6	7,6	25,3	2,5	14,4	3	5,9	6,9
291	0,7		1,0	0,5	2,3	10,8	38,2	50	50			
298						2,2	9,6			6 ,3	9,2	10,9

TABLE X.11b - Crop morphological and physiological data and soil water contents measured at Site B, 1983.

DOY	CROP HEIGHT	GROWTH STAGE	ROOT DEPTH	LAI MEAS	LAI CALC	LEAF WATER POTENTIAL MEASURED 06H00	LEAF WATER POTENTIAL MEASURED 12H00	LEAF WATER POTENTIAL CALCULATED 06H00	LEAF WATER POTENTIAL CALCULATED 12H00	MEASURED LAYER θg ,0-,3	MEASURED LAYER θg ,3-,6	MEASURED LAYER θg ,6-,9
	(m)		(m)			(bar)	(bar)	(bar)	(bar)	(%)	(%)	(%)
186	0,1	Tillering	0,2		0,5			0,3	6,6	4,3	6	6
193	0,1		0,2		0,7	3,3		0,1	6,5			
200	0,2		0,3	0,8	0,7	5	13,6	0,4	5,6	5	6,5	7
207	0,2		0,3	0,7	0,8	1,5		0,2	2,8	9,5	8,2	6,2
216	0,2		0,4	1,3	0,9	3,5	14,8	0,4	8,2	4,5	6,3	6,2
221	0,2		0,5	1,8	1	0,9	17,8	0,1	6,9	3,6	5,3	5,3
229	0,3		0,6	2,6	1,3		16,9	0,2	8,2	4,5	6,5	6,1
235	0,3		0,8	3,2	2,2	1,5	15	0,2	9,5	3,1	5,2	5,1
242	0,4		0,9	2,6	3,2	7,8		1,9	13,2	2,7	3,7	3,8
249	0,4	Heading	0,9		4	13,2	22,4	5,3	15	15,1	6,9	3,4
256	0,7		1	2	5,6	17,3	25,3	1,5	11,5	4,3	6	6,1
263	0,8	Flowering	1,3	4,1	6,8	17,3	24	1,8	11,5	2,5	4,1	3,9
270	0,7		1,3	3	7		21,6	4	13,2	5,5	6,2	5,6
277	0,7		1,5	1,3	5,6	5,3	24	2,6	14,6	2,3	4,4	3,1
291	0,8		1,7		3,1			5,1	2,5			
298										2,4	5,1	4,8

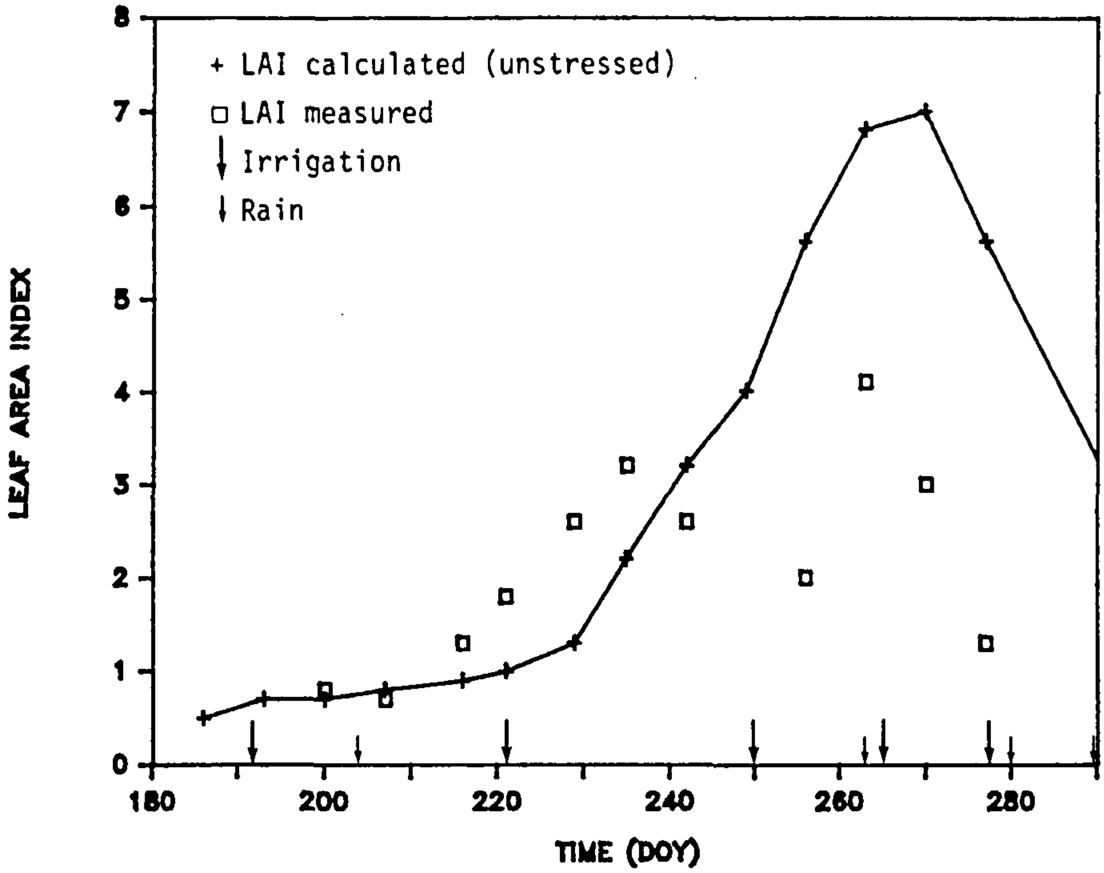


FIG. X.12a - Measured and simulated leaf area indices, Site B, 1983

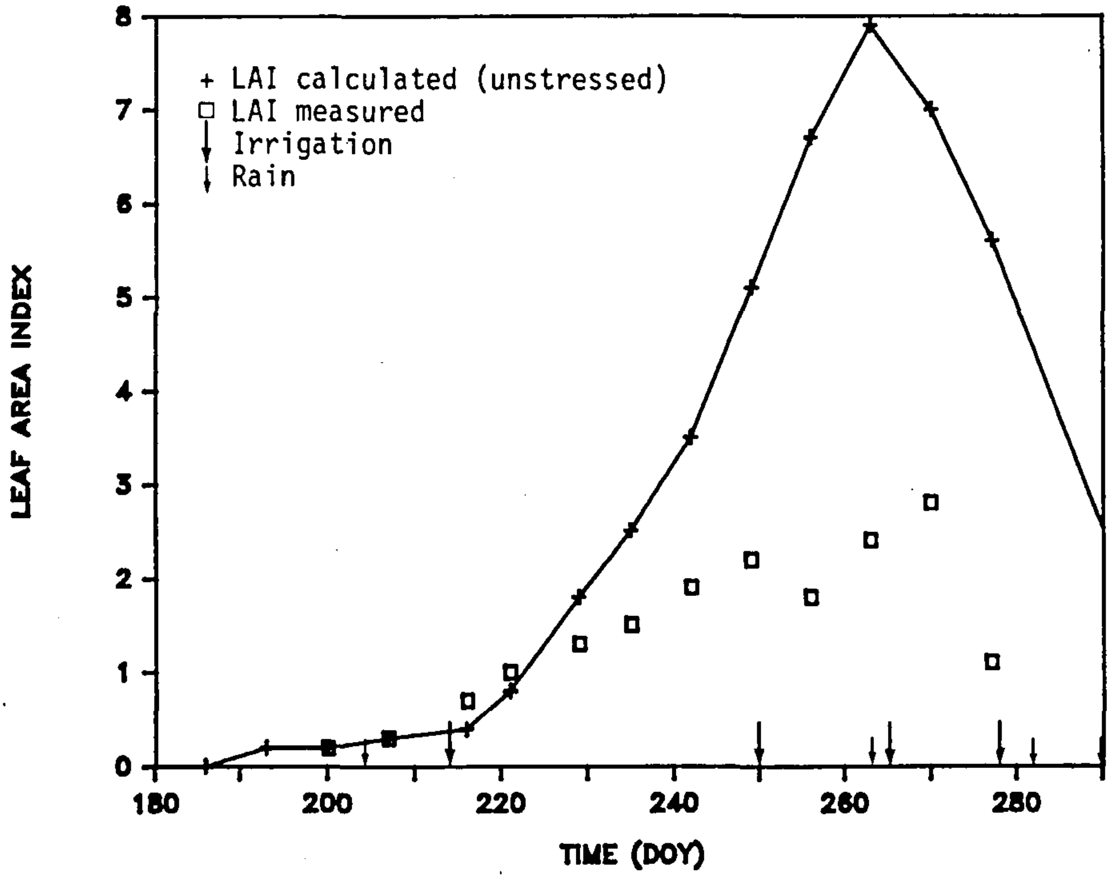


FIG. X.12.2 - Measured and simulated leaf area indices, Site A, 1983.

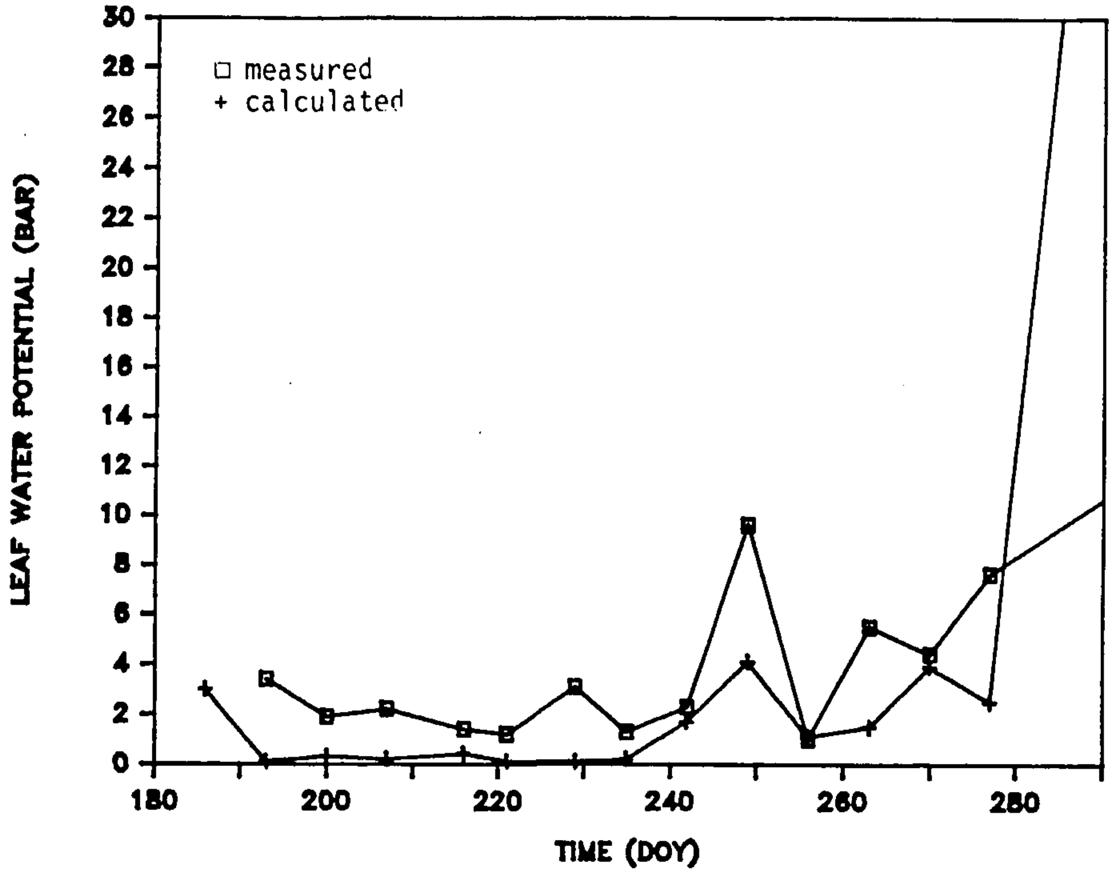


FIG X. 13a (1) - Pre-dawn leaf water potential at Site A, 1983.

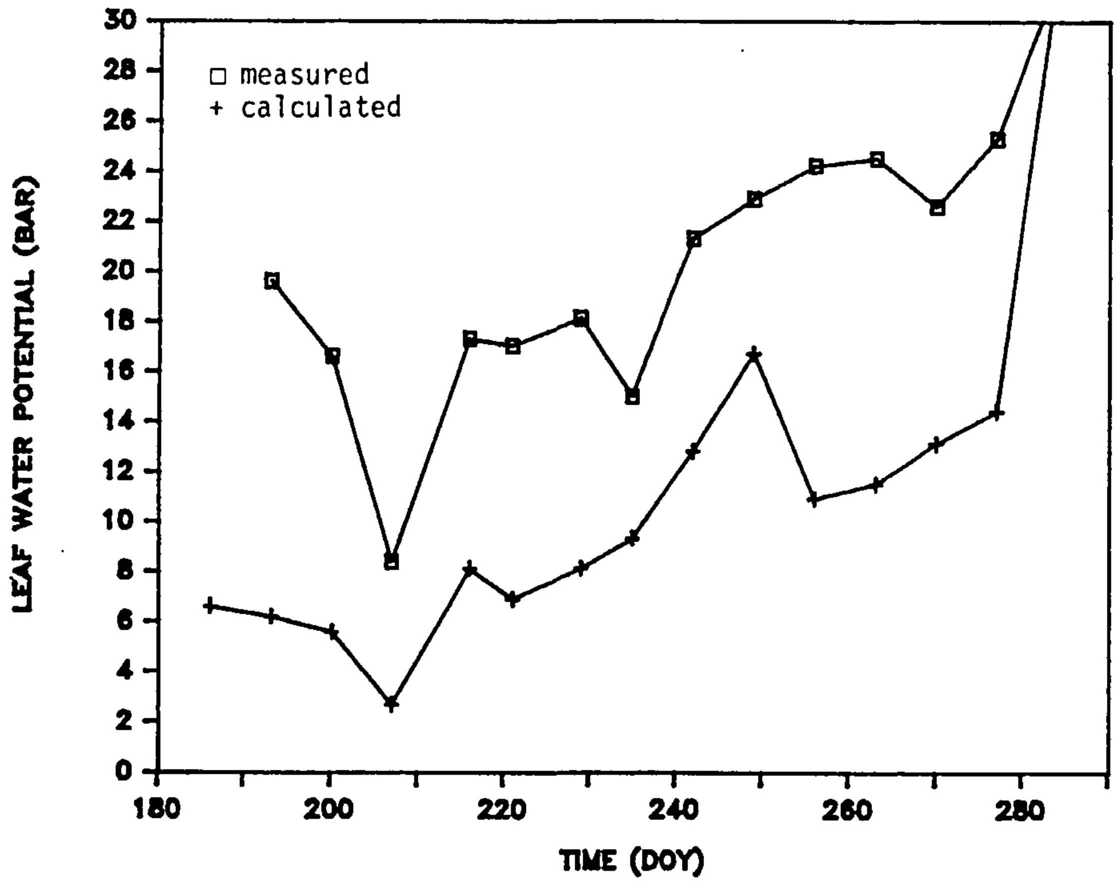


FIG. X.13a (2) - Noon leaf water potential at Site A, 1983.

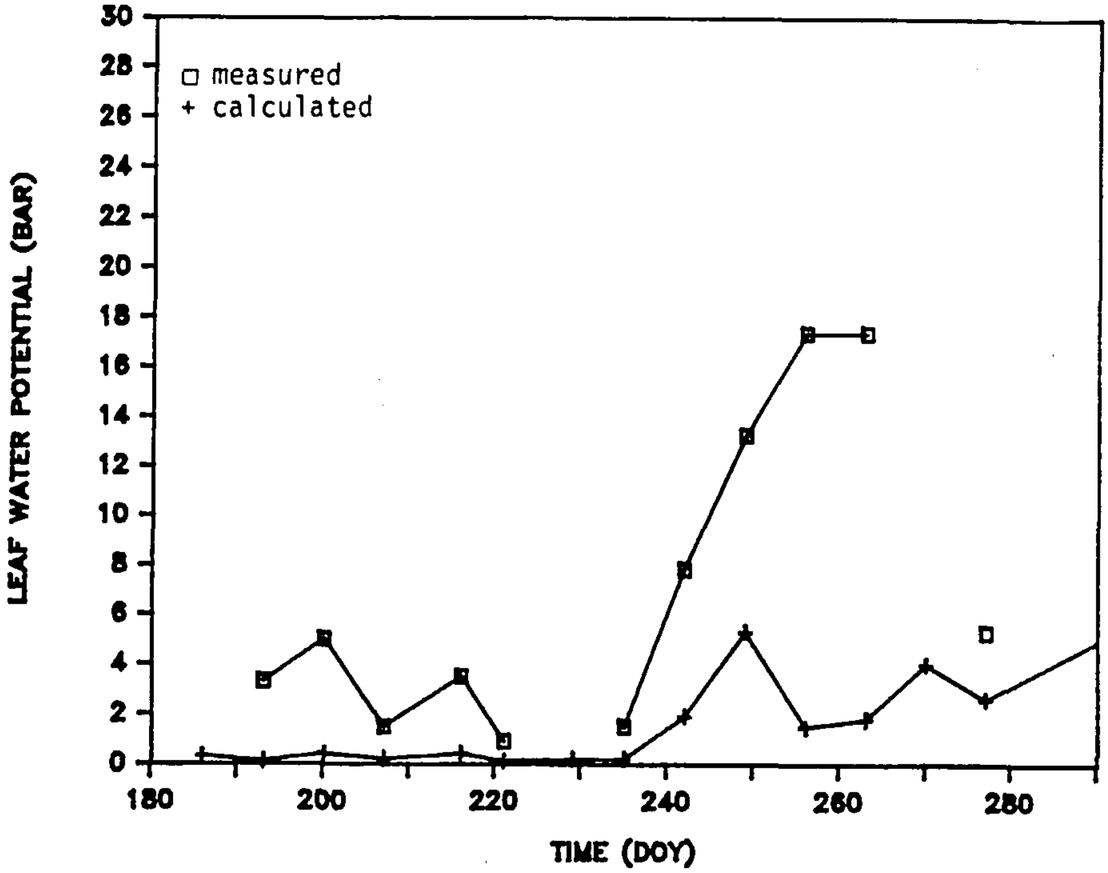


FIG. X.13b(1) - Pre-dawn leaf water potential at Site B, 1983.

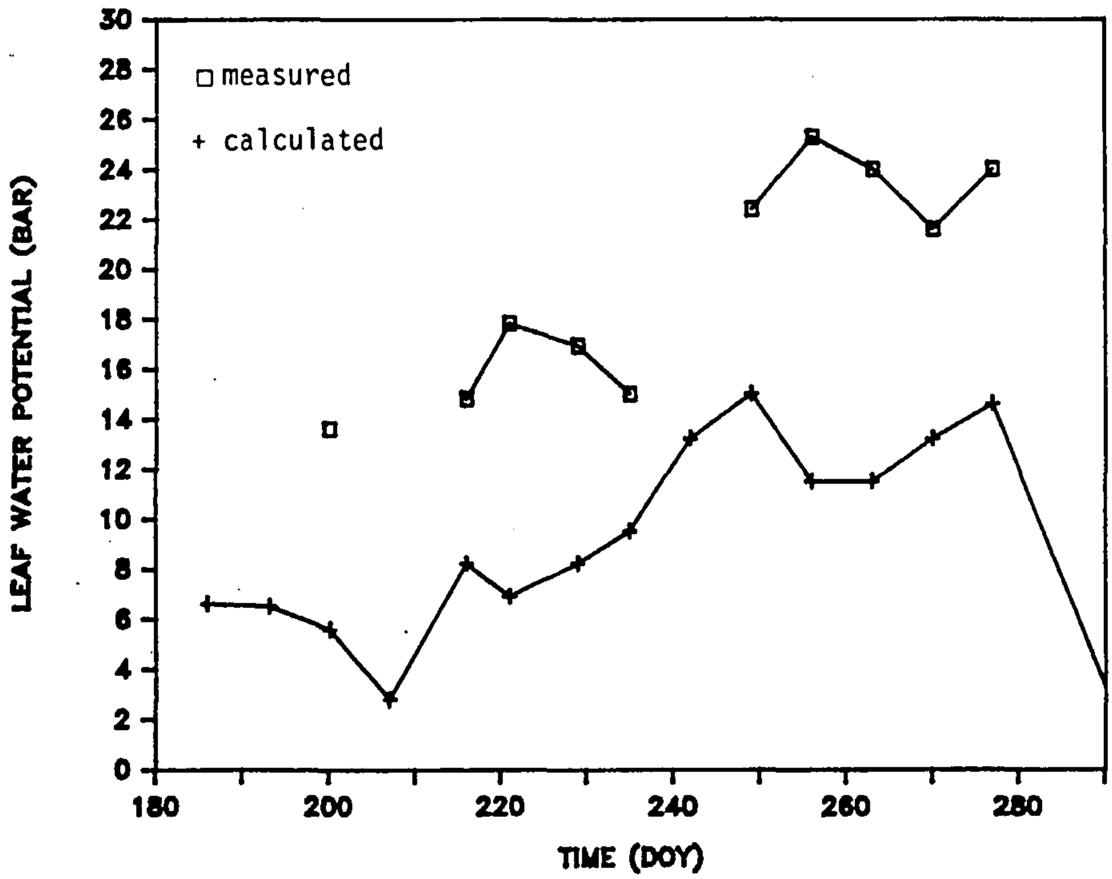


FIG. X.13b (2) - Noon leaf water potential at Site B, 1983.

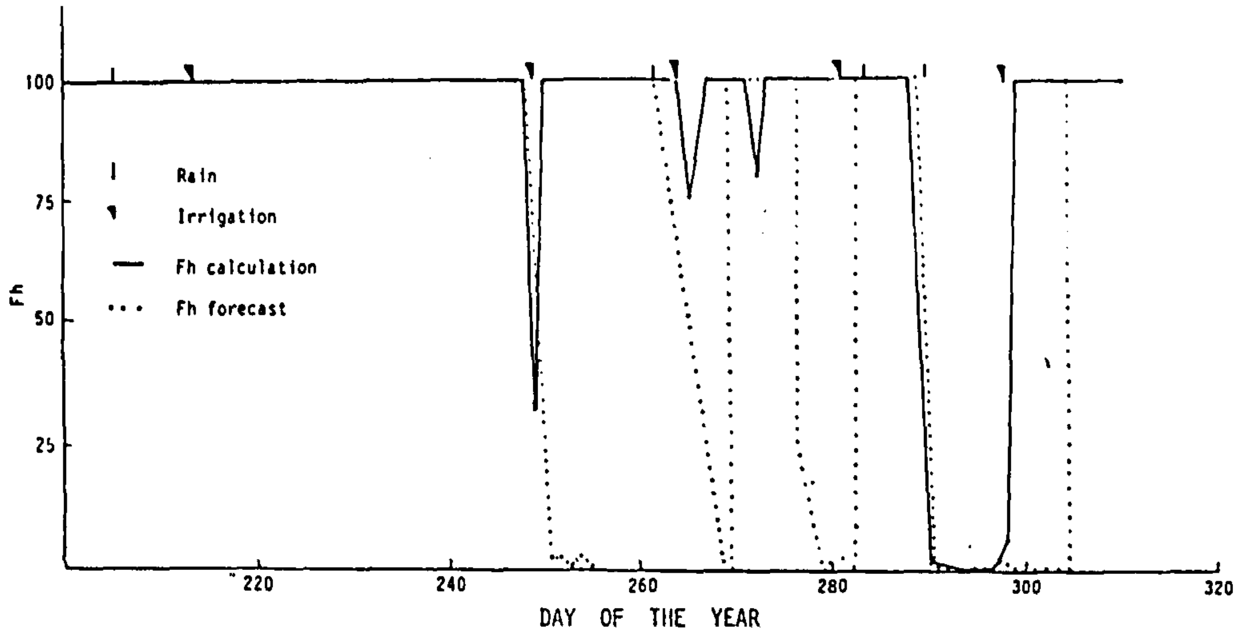


FIG. X.14a - Scenario of the hydraulic scheduling factor, Fh, on Site A, 1983 for the UOFS plot.

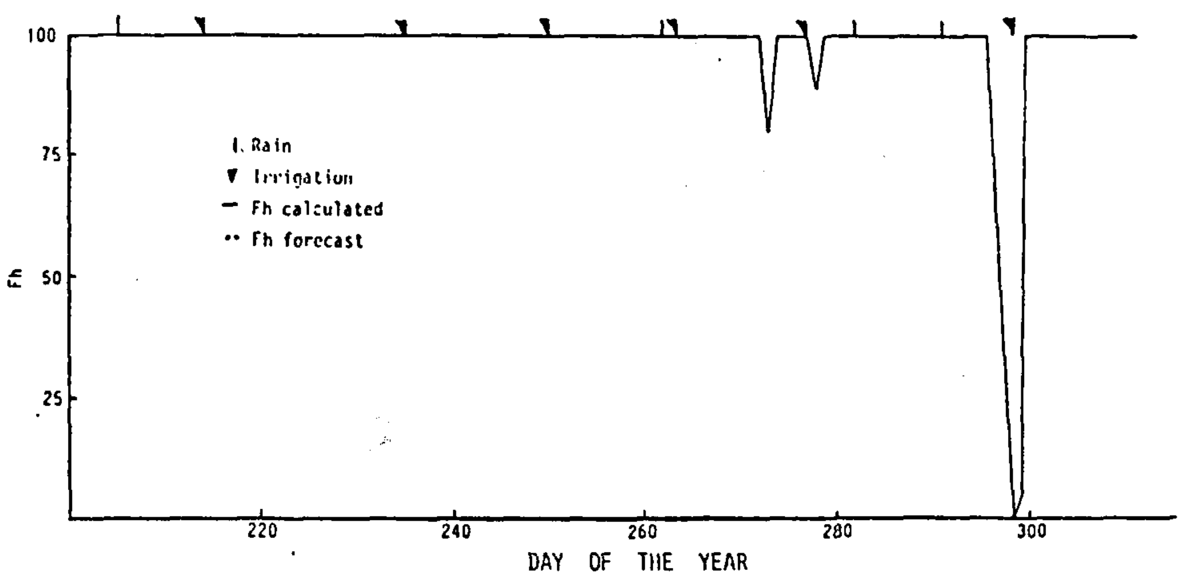


FIG. X.14b - Scenario of the hydraulic scheduling factor, Fh, on Site A, 1983 for the farmer plot.

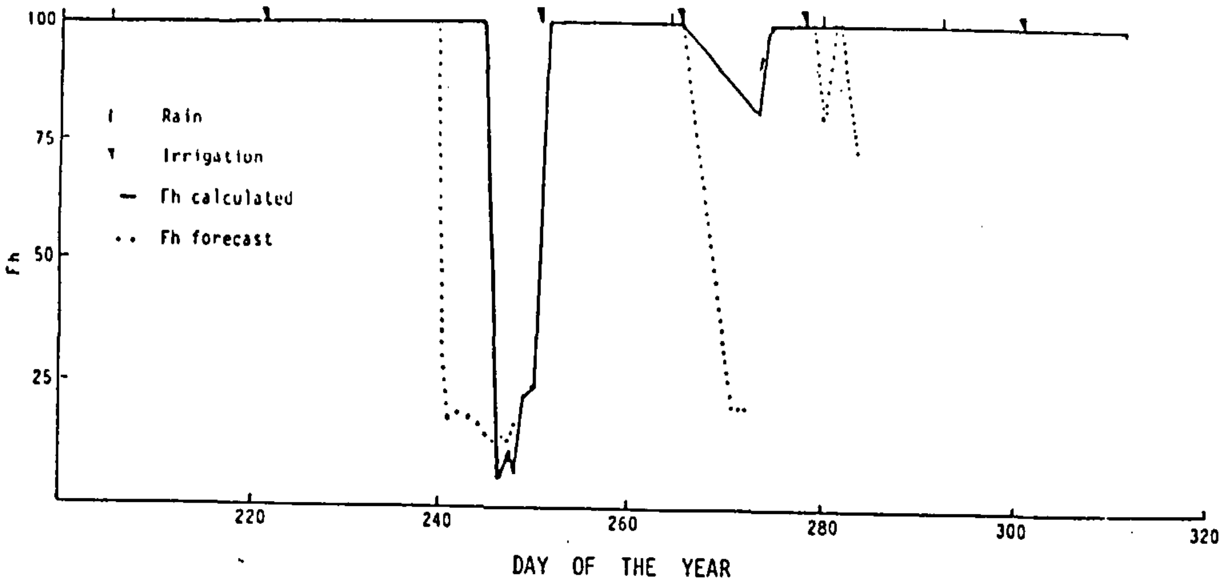


FIG. X.15a - Scenario of the hydraulic scheduling factor, Fh, on Site B, 1983 for the UOFS plot.

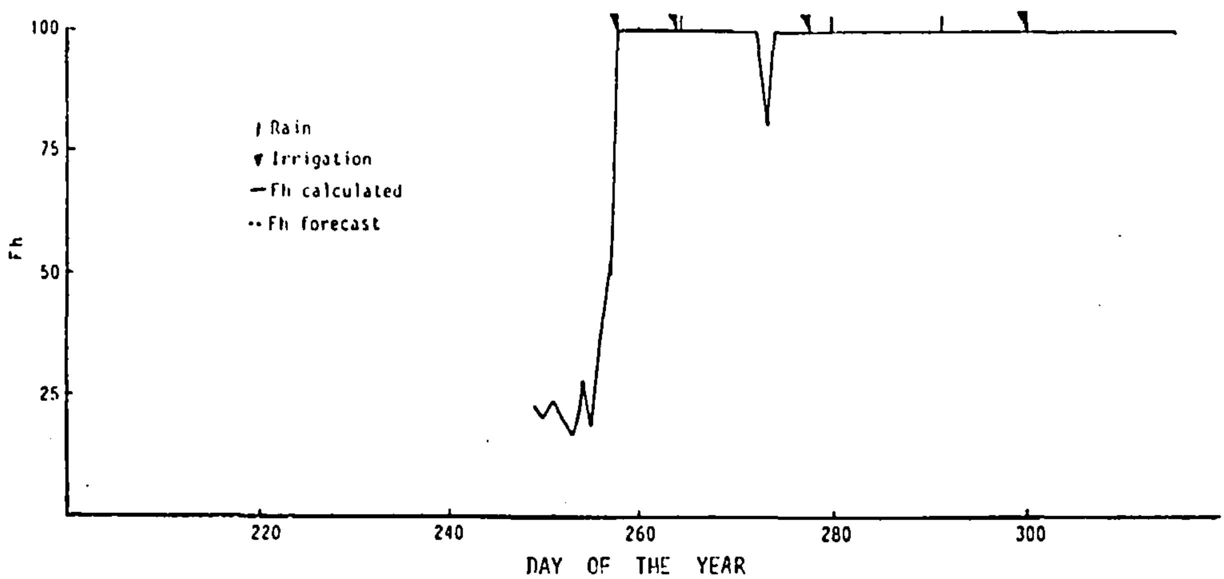


FIG. X.15b - Scenario of the hydraulic scheduling factor, Fh, on Site B, 1983 for the farmer plot.

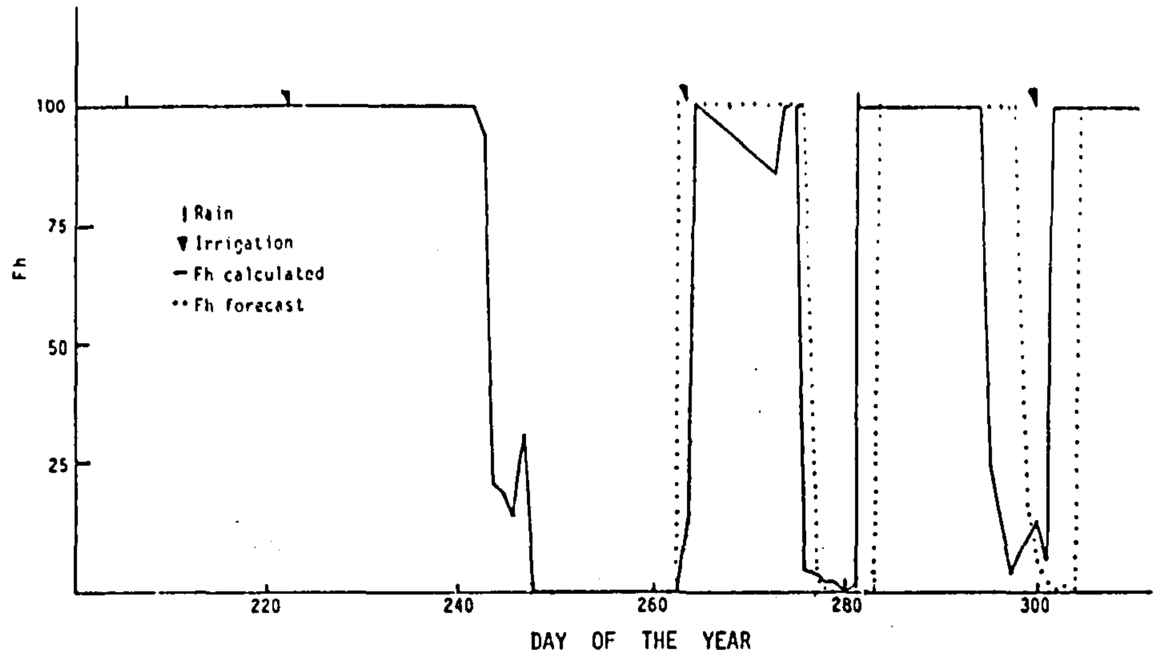


FIG. X.16a - Scenario of the hydraulic scheduling factor, Fh, on Site C, 1983 for the UOFS plot.

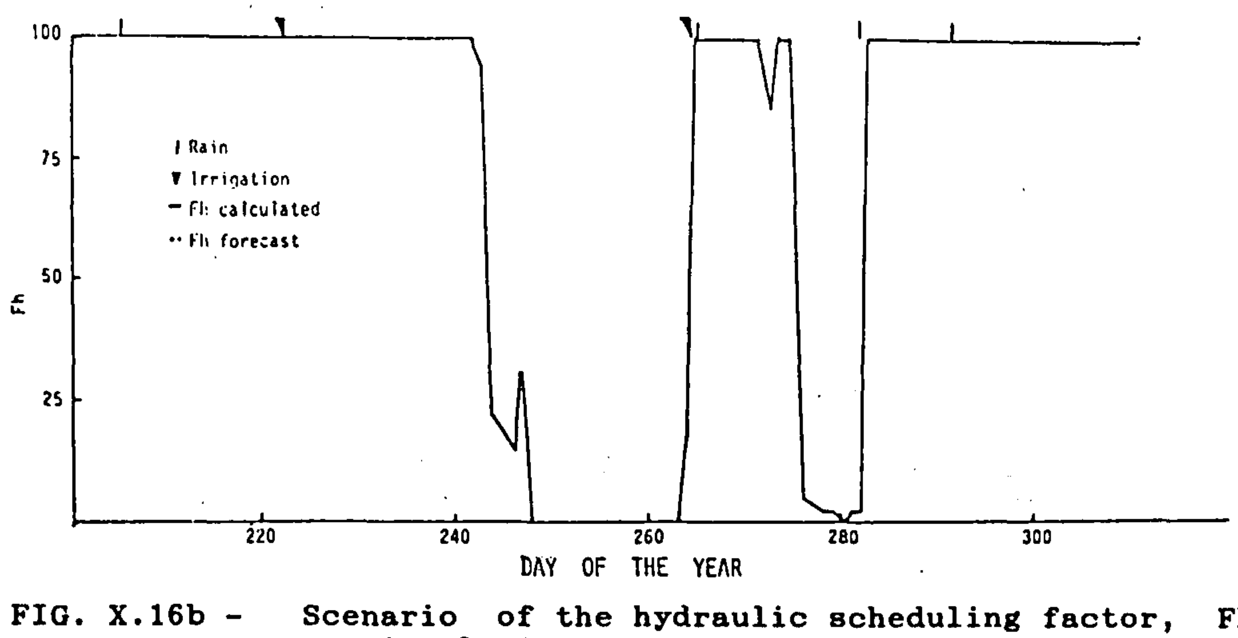


FIG. X.16b - Scenario of the hydraulic scheduling factor, Fh, on Site C, 1983 for the farmer plot.

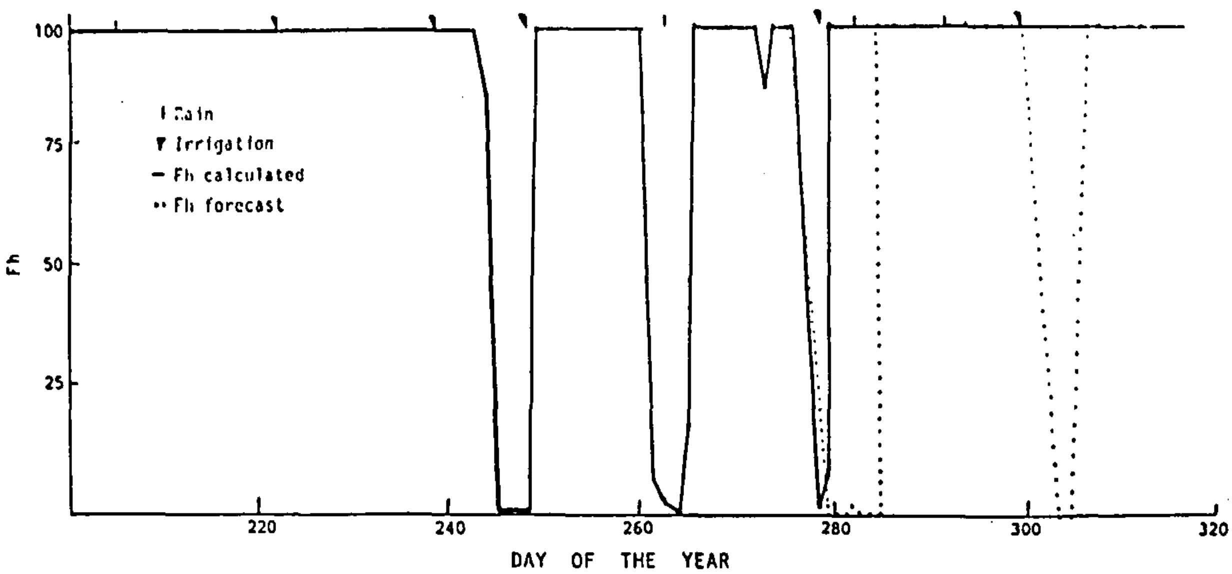


FIG. X.17a - Scenario of hydraulic scheduling factor, Fh, on Site D, 1983 for the UOFS plot.

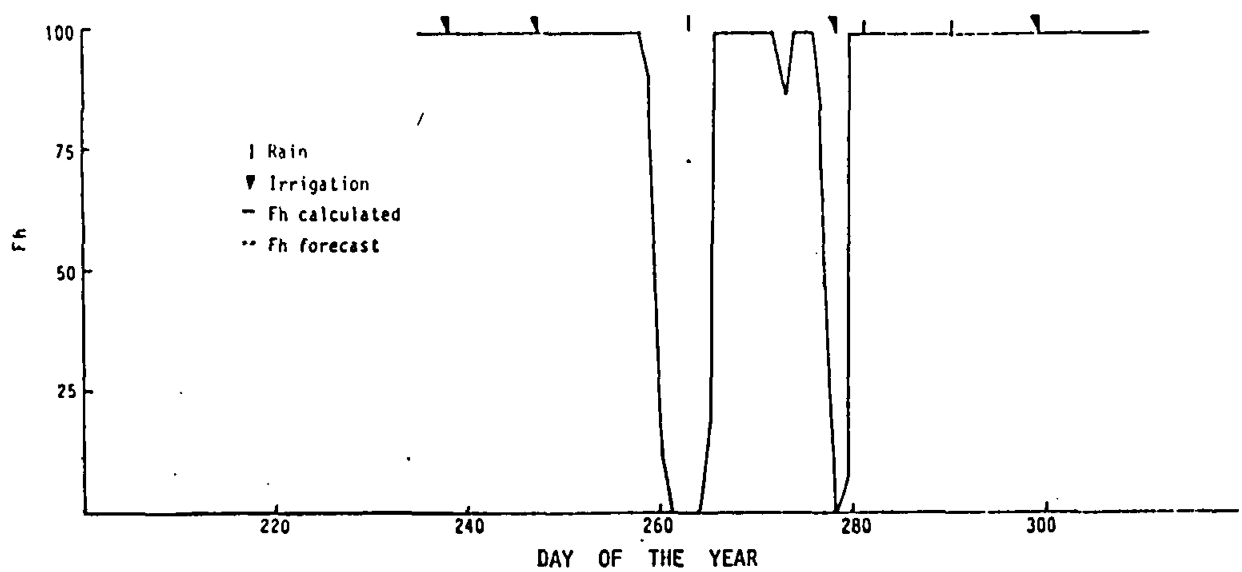


FIG. X.17b - Scenario of hydraulic scheduling factor, Fh, on Site D, 1983 for the farmer plot.

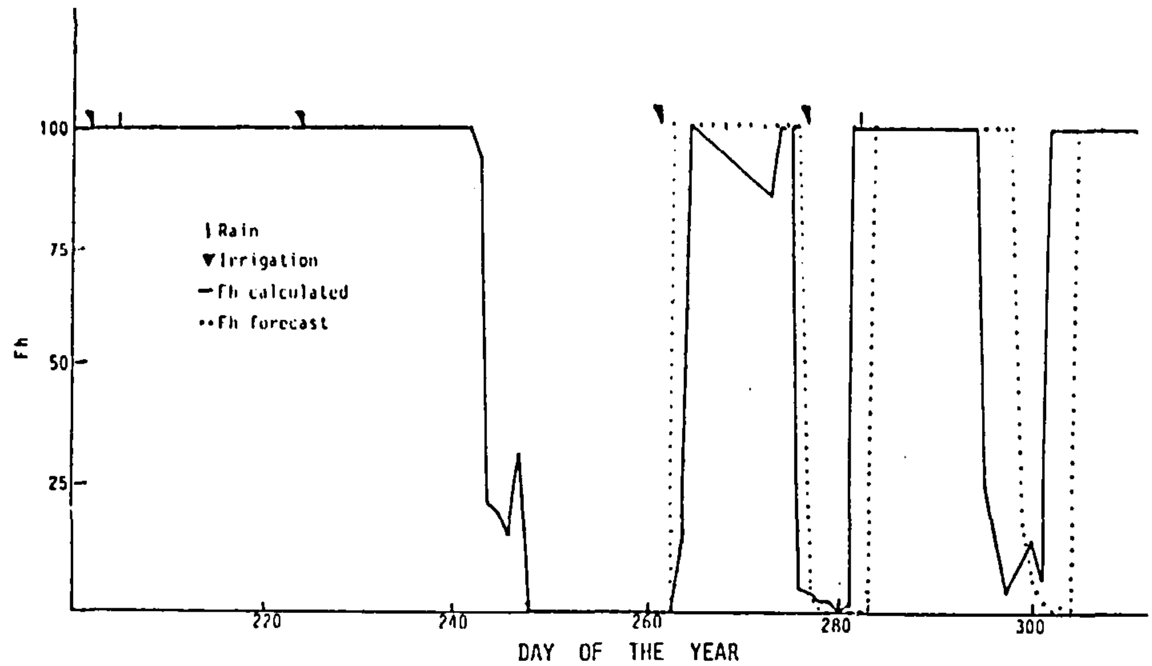


FIG. X.18a - Scenario of the hydraulic scheduling factor, Fh, on Site E, 1983 for the UOFS plot

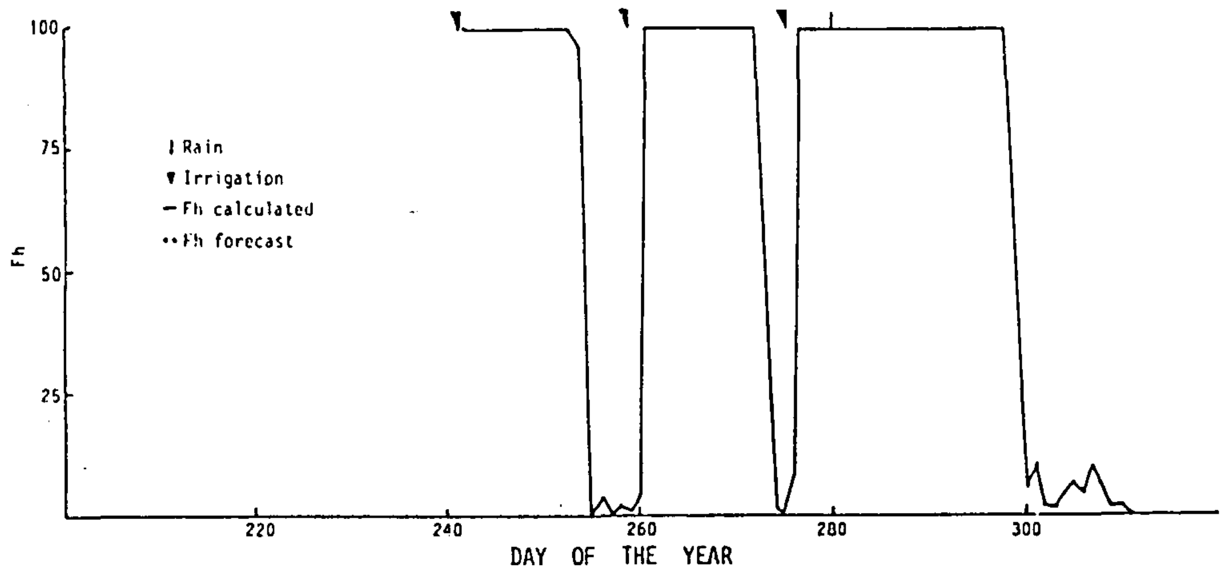


FIG. X.18b - Scenario of the hydraulic scheduling factor, Fh, on Site E, 1983 for the farmer plot.

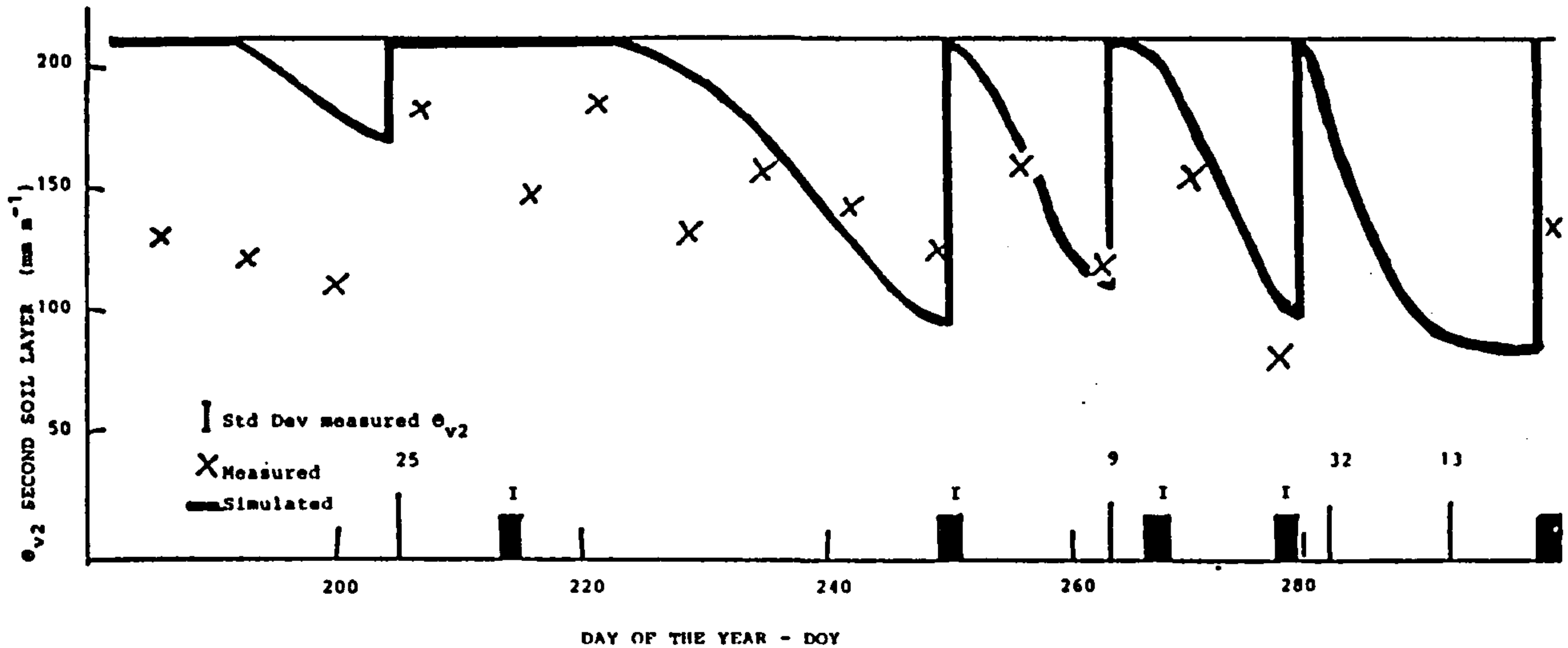


FIG. X.19 - Gravimetrically measured and simulated values of the volumetric water content in the second soil layer, θv_2 at Site A, during 1983.

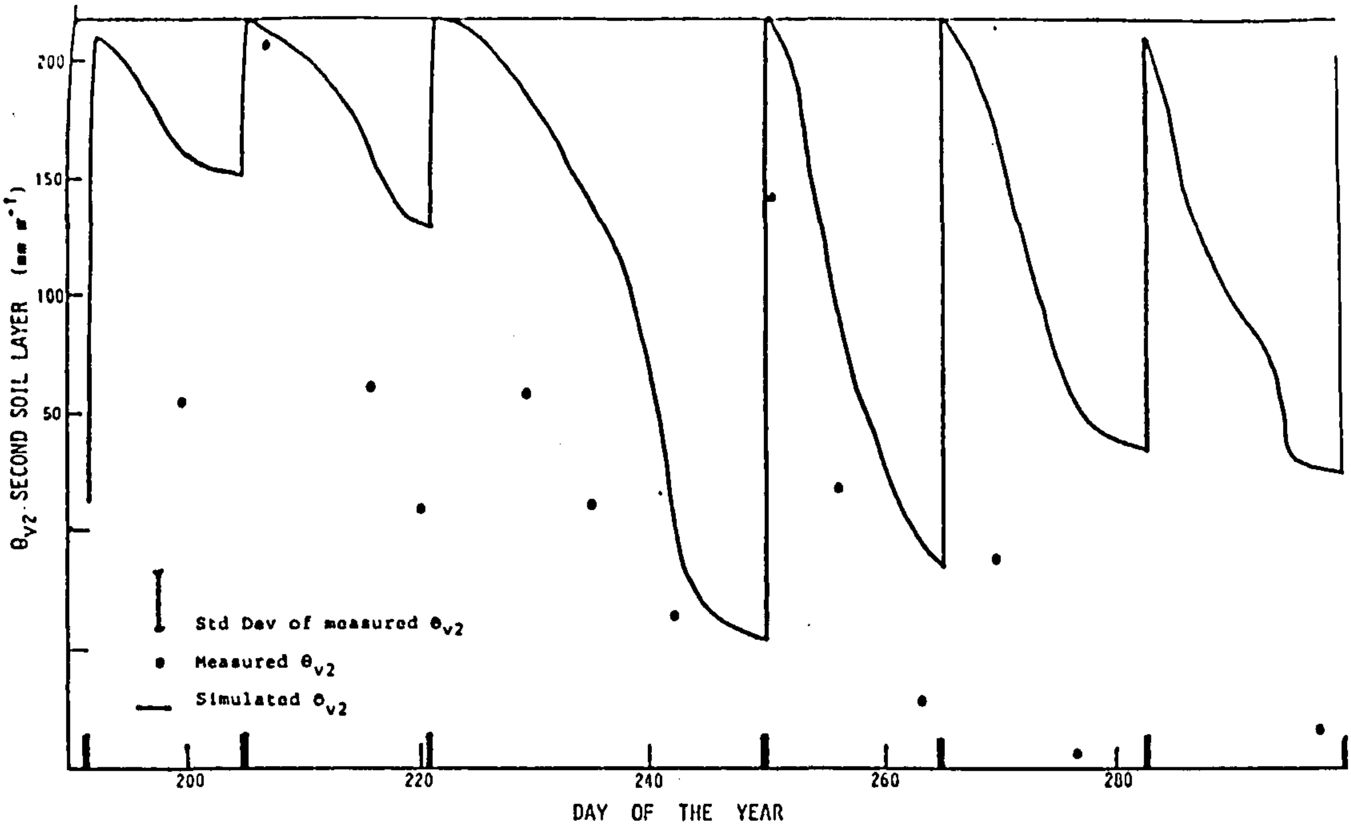


FIG. X.20a - Gravimetrically measured and simulated values of the volumetric water content in the second soil layer θv_2 , at Site B, during 1983.

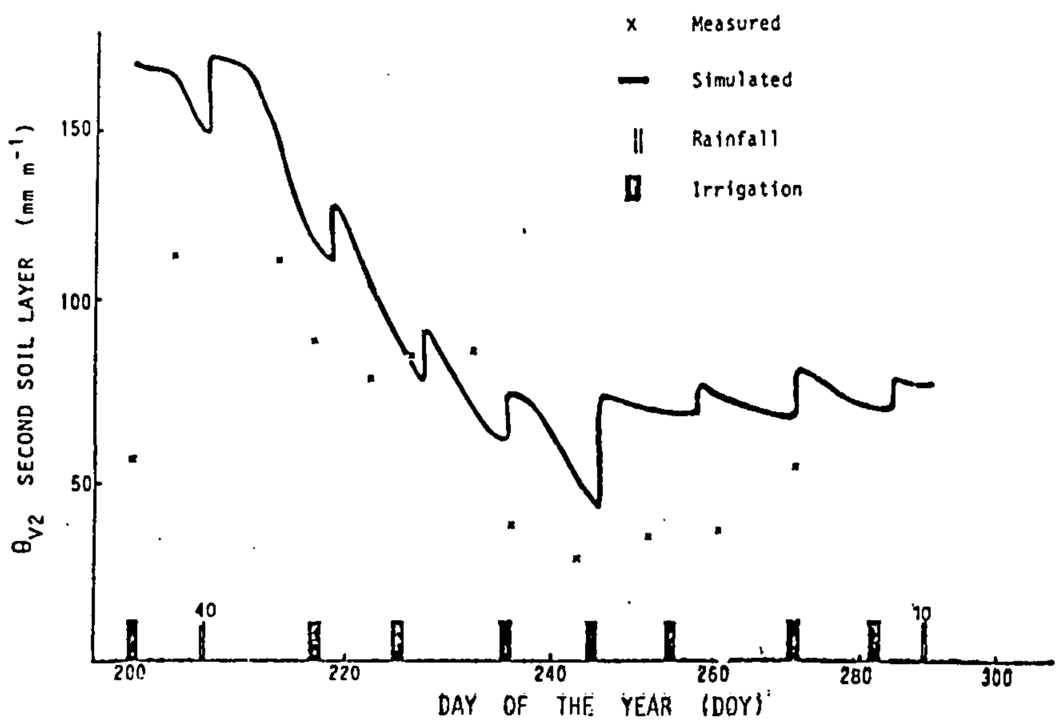


FIG. X.20b - Gravimetrically measured and simulated values of the volumetric water content in the second soil layer, θv_2 , at Site F, during 1983.

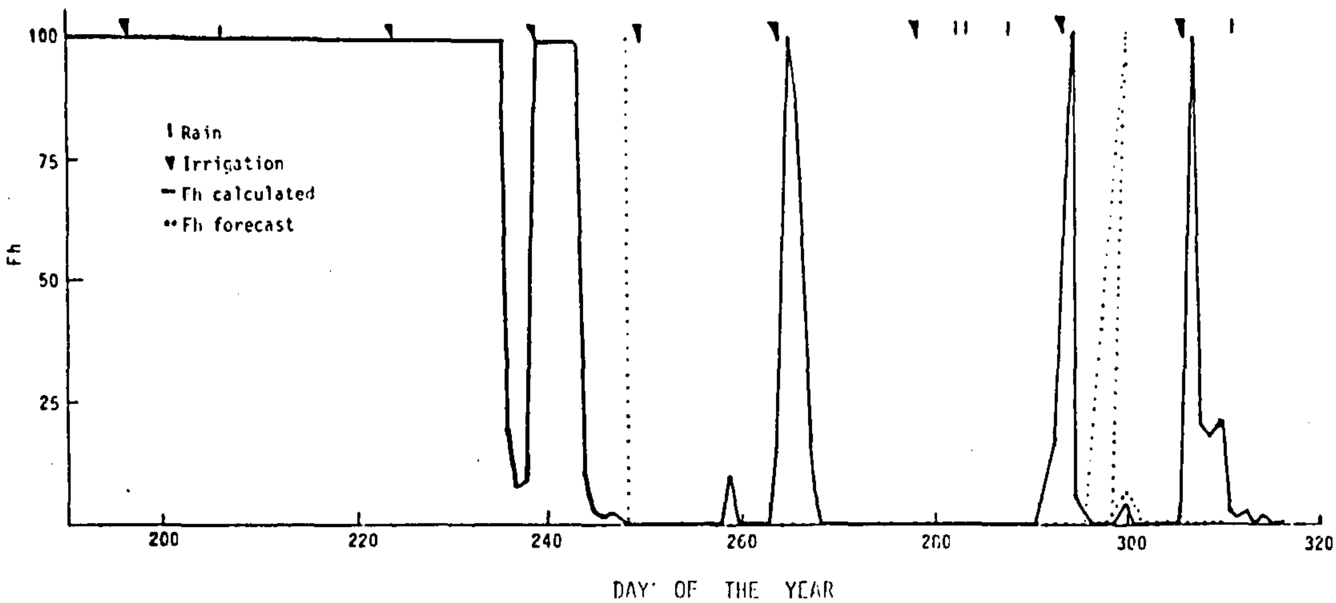


FIG. X.20c - Scenario of the hydraulic scheduling factor, Fh, on site F, 1983.

TABLE X.20 - Cultivation practices adopted by the different farmers during 1982.

SITE	TIME OF PLANTING CALENDER	DOY	PLANT DENSITY (m)	(kg/ha)	ROW WIDTH (mm)	(m)	CULTIVAR	SOIL DESCRIPTION	IRRIGATION PLOT SIZE (m)	FERTILIZER
A	82.06.25	176	223	85	167	6	T4	Mangano loamy sand: 10% clay, 2% silt, 1,8% course sand, 69% fine sand	6,5 x 200	
B	82.06.16	167	383	150	167	6	T4	Sand: 94% sand, 6% clay	6,5 x 287	300 kg/ha 3.2.1 (25) 500 kg/ha Amonium Sulphate
C	82.06.23	174	383				T4	Sand: 94% sand 6% clay	6,5 x 118	
D	82.06.04	155	383				T4		6,5 x 90	

TABLE X.21 - Cultivation practices during 1983.

Row widths on all farms were 167 mm except for Site C where a row width of 200 mm was used.

A - HARTSWATER

Cultivar : SST 44 255 plants/ha

Fertilizer : 350 kg/ha 3.2.4.(25)
250 kg/ha ASN (27)
100 kg/ha ASN (27) top dressing

B - MAGAGONG

Cultivar : T4 258 plants/ha

Fertilizer : 200 kg/ha 2.3.4.(30)
150 kg/ha Ammonium Sulphate applied before planting (June 11, 1983.
300 kg/ha Ammonium Sulphate top dressing applied on July 11, 1983.

C - TADCASTER

Cultivar : T4 278 plants/ha

Fertilizer : 250 kg/ha 3.2.1 (25) applied before planting.
250 kg/ha Ammonium Sulphate top dressing applied with the first irrigation after planting, viz. August 10, 1983.

D - TADCASTER

Cultivar : T4 436 plants/ha

Fertilizer : 350 kg/ha 3.2.1 (25)
460 kg/ha ASN (27)
All the fertilizer was applied before planting.

E - MAGAGONG

Cultivar : Zaragoza 266 plants/ha

Fertilizer : 500 kg/ha 3.2.1 (25)
300 kg/ha Ammonium Sulphate
270 kg/ha Ammonium Sulphate top dressing applied on August 30, 1983.
